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UNIVERSITÉ DE MONTRÉAL

DEVELOPING A RUN-TIME COUPLING BETWEEN ESP-R AND TRNSYS

ROMAIN JOST

DÉPARTEMENT DE GÉNIE MÉCANIQUE

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DEVELOPING A RUN-TIME COUPLING BETWEEN TRNSYS AND ESP-R

présenté par : JOST Romain

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M. BERNIER Michel, Ph.D., président

M. KUMMERT Michaël, Ph.D., membre et directeur de recherche

M. BEAUSOLEIL-MORRISON Ian, Ph.D., membre

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RESUME

Dans le cadre de la réduction de l'énergie consommée par les bâtiments, il est essentiel d'être rigoureux dans leur modélisation. Pour ce faire, un grand nombre de logiciels de simulation existe, mais, ces outils sont pour la plupart spécialisés dans un domaine particulier et ne permettent pas toujours de réaliser une analyse complète. Étant donné que tous les domaines (chauffage, climatisation, ventilation, éclairage, acoustique) sont interdépendants, il n'existe pas de plateforme de simulation permettant de couvrir toutes les particularités d'un système avec la même flexibilité, et il est nécessaire de procéder à des combinaisons ou des couplages de logiciels. Ce mémoire décrit la réalisation d'un couplage au niveau de l'exécution entre TRNSYS et ESP-r.

Afin de réduire au maximum les modifications apportées aux codes sources et façonner un outil durable face au développement de chacun des deux logiciels dans le futur, le couplage se fait principalement à l'aide de nouveaux composants recevant et envoyant des données à l'autre programme. L'échange de données est réalisé par une structure à DLLs multiples. En plus de celles de TRNSYS et ESP-r, une troisième DLL chargée d'appeler les deux autres et de contrôler l'échange d'information a été créée. Celle-ci supervise également le contrôle de la convergence et assure l'avancement simultané des deux programmes. Cette DLL qui joue le rôle d'intermédiaire entre les deux logiciels (middleware) est appelée l'Harmonizer.

Une nouvelle catégorie de composants a été mise en place pour le logiciel TRNSYS. Il s'agit des Types Échangeurs de Données (Data Exchanger Types). Ces composants fonctionnent de manière identique aux Types classiques en communiquant à travers leurs entrées et sorties, mais ils sont également capables de forcer le solveur à poursuivre les itérations d'un pas de temps. Cette fonctionnalité est essentielle afin d'obliger TRNSYS à faire de nouveaux calculs lorsque qu'il y a convergence au niveau interne mais que ce n'est pas le cas pour l'autre logiciel. Un composant de cette nouvelle catégorie, appelé Type 130, a été créé spécialement pour le couplage avec ESP-r. Ce dernier assure la liaison et l'échange de données entre l'Harmonizer d'une part et les composants du système dans TRNSYS de l'autre.

Du point de vue de l'utilisateur, il n'y a que peu de changements entre le fait de réaliser un modèle pour une co-simulation et celui pour une simulation n'utilisant qu'un seul logiciel. Les fichiers d'entrée et de sortie sont identiques à ceux d'une simulation standard, et ce pour les deux

logiciels. L'unique fichier additionnel à configurer est le fichier d'entrée de l'Harmonizer contenant les paramètres de la co-simulation.

Ce mémoire décrit le travail réalisée par l’équipe du projet et les contributions spécifiques de l’auteur sont identifiées dans le texte.

ABSTRACT

Rigorous modeling is essential to design buildings and deliver the next advances in energy efficiency and on-site renewable energy production. A great variety of energy simulation programs exists but they are, for the most part, specialized in one particular domain and they do not allow a complete analysis. Because all domains (heating, cooling, ventilation, lighting, acoustic) are interconnected and there is no global simulation environment existing that covers all of the system particularities with the same flexibility, it is often appropriate to proceed with software combination and/or coupling. This Master thesis describes the implementation of a run-time coupling between TRNSYS and ESP-r.

In order to minimize the modifications to the source codes and create a tool able to support future development of each program, new components that receive and pass data to the other program were implemented in the two software programs. A multi DLL structure enables the coupling and exchange of information. A third piece of software, the Harmonizer, launches TRNSYS and ESP-r DLLS and manages the exchange of data. It is also responsible of the convergence handling and controls that both programs march through time together time step after time step.

A new category of components, the Data Exchanger Types was implemented in TRNSYS. These components can work as standard TRNSYS Types and exchange data through their inputs and outputs but they can also impose the solver to continue iterating. This capability is essential to force TRNSYS to do more calculations at a specific time step when it has converged but co-simulation convergence requires more iterations. A component of this new category, Type 130, was created specifically for the coupling with ESP-r. Type 130 exchanges data with the Harmonizer on one side and with the TRNSYS network of Types on the other side.

Testing of basic data exchange validates the data exchange method and the coupling. The co-simulator is able to simulate a complete system with a building modeled in ESP-r and the energy system in TRNSYS.

On the user perspective, there are few changes in implementing a co-simulation model in comparison to a simple simulation model using only one program. Users with some knowledge of both programs will be familiar with the steps required to perform a co-simulation. The input

and output files are the same for the two programs as a standard simulation. Settings of the co-simulation are defined in the Harmonizer input.

This Master Thesis describes the work of the project team, referred to as the Design Team in the text. Specific contributions from the author are identified in the document.

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LIST OF ABBREVIATIONS

ACC	Air Coupling Component
BCVTB	Building Control Virtual Test Bed
BPS	Building Performance Simulation
CV	Control Volume
DDS	Derived Data Structure
DLL	Dynamic-Link Library
FCC	Fluid Coupling Component
HCC	Hydronic Coupling Component
HR	Humidity Ratio
HVAC	Heating, Ventilation and Air-Conditioning
IAQ	Indoor Air Quality
NMF	Neutral Model Format
NZEB	Net Zero Energy Building
OS	Operating System
PID	Proportional Integral Derivative
PV	Photovoltaic
TCC	TRNSYS Coupling Component

INTRODUCTION

Designing the next generation of energy efficient buildings with on-site renewable energy production to meet the "Net Zero Energy" target requires the use of integrated simulation tools capable of dealing with the level of complexity in the building and the associated mechanical and electrical systems.

A great variety of efficient Building Performance Simulation (BPS) tools exist on the market but they are, for the most part, specialized in one particular domain and lack flexibility or capabilities in other domains. This may affect the accuracy of simulations results as it is sometimes difficult to perform a whole system analysis with one tool. ESP-r and TRNSYS are both powerful simulation programs but their different implementation approaches gave them different strengths. ESP-r is particularly efficient in modeling building physics whereas TRNSYS is more flexible in treating elaborated mechanical and electrical systems. Because all domains (heating, cooling, ventilation, lighting, acoustic) are interconnected and there is no global simulation environment existing that covers all particularities of a system with the same flexibility, combining or coupling simulation programs is often required.

This document presents the work on the development of a run-time coupling between TRNSYS and ESP-r. With funding and guidance from Natural Resources Canada, a Design Team composed of 6 people from Carleton University, Ottawa, École Polytechnique de Montréal, and Thermal Energy System Specialists (TESS), Madison (USA), completed this project. Tasks were divided between the members: the Carleton University part of the team worked on the implementation of the coupling on the ESP-r side and on the implementation of the middleware (known as the Harmonizer), team members from Polytechnique Montréal and TESS carried out modifications to the TRNSYS source code. The whole Design Team was involved during all phases of the project and provided inputs to development work and to the overall coupling strategy, under the supervision of the project leader at Carleton University. This Master thesis describes the methodology and results of the project, with more emphasis on the TRNSYS side. The specific contributions of the author, who was the lead developer for TRNSYS source code changes, are identified in the text.

Thesis organization

First, this document presents Building Performance Simulation combinations and couplings described in the literature. The main approaches are compared. Chapter 1 gives an overview of the couplings methods from basic links and collecting external data to integration of source code and more complex run-time coupling. Chapter 2 presents the calculation methodologies of TRNSYS and ESP-r and a description of the co-simulation approach selected by the Design Team. Chapter 3 details the implementation of the coupling and the modifications to each program source code. The ESP-r part is briefly commented, while TRNSYS source code changes are presented in details with the source code provided in an Annex.

Chapter 4 reports on the various tests that were performed to confirm the proper operation and the usefulness of the proposed co-simulator. Results demonstrating the coupling capabilities from the very basic data exchange tests to complete co-simulations are presented there. Chapter 5 describes how to perform co-simulations from a user perspective, and leads to the final conclusions of this work.

CHAPTER 1 LITERATURE REVIEW

This introductory chapter presents an overview of the current work in building performance simulation and couplings between software programs. First, the need for integrating building simulation programs and different approaches are presented. Then, different coupling methods are discussed.

1.1 Building simulation

The design of buildings and mechanical systems aims at saving energy while maintaining or improving occupant comfort. Integrated Building Performance Simulation (BPS) tools play an important role in assessing the energy and economic performance of design options. They must be efficient and adapted to more and more demanding building standards, codes and certification programs. The end of the section presents two of the major programs in that domain, TRNSYS and ESP-r.

1.1.1 Net Zero Energy Buildings

Design of buildings in the near future will be oriented towards the Net Zero Energy Building (NZEB) target. Stricter energy efficiency regulations are already taking shape for the next decades. In the USA, the goal of net zero for every new commercial building is set to 2030 by the Energy Independence and Security Act of 2007 (EISA 2007). The European Union is even more demanding in the reduction of energy consumption with the Energy Performance of Building Directive (EPBD) that imposes a neutral energy balance for every new construction by 2020. These texts are ambitious, however they lack precision on the definition of Net Zero Energy buildings, as well as on the methodology to design those types of buildings (Marszal et al., 2011). Currently, several definitions of NZEB exists (Torcellini, Pless, & Deru, 2006) but in order to apply these new laws, a rigorous design methodology will be needed. This will also require the creation of new buildings and systems simulation tools and/or modifications of the current ones to respond efficiently to these energy saving constraints.

Several methods of defining the total energy balance of buildings already exist. The majority uses the primary energy consumption in their calculations. They differ for example on the period of simulation: they mostly consider a period of one year but this period can vary from a month to the entire life cycle. A few of these approaches only consider thermal and electrical energy used to operate the building, while others extend the energy balance to account for the energy required during the construction process (including embodied energy for all construction materials). A commonly used indicator of the net zero energy target is the ratio between the building energy consumption and the on-site renewable energy production. There is no consensus on a "best" methodology at this stage, each of them focuses on slightly different aspects of the problem. The design of NZEBs and the evaluation of their performance must be adapted to the selected methodology.

BPS tools must be adapted to these requirements and allow to improve energy efficiency at the building level, as well as to integrate advanced Heating, Ventilation and Air-Conditioning (HVAC) systems and on-site renewable energy systems.

1.1.2 Integrated simulations

Rigorous modeling is essential to design buildings that will meet the very ambitious energy efficiency targets described above. It is essential to treat buildings and systems, at the same time to get the best optimization (Hensen, Djunaedy, Radošević, & Yahiaoui, 2004). Using a systemic modeling approach during the design phase, allows harmonizing all of the key domains of building construction from the engineering part to the architectural part. This leads to a design optimizing both the energy consumption and the comfort of occupants.

Bazilian et al. (2001) illustrated the need of integrated simulations in modeling co-generation photovoltaic collectors and the strong link between architecture and system design. A façade configuration with pre-heating of the supplied air is presented by the author who explained that such a system would also impact substantially the architectural domain. It is therefore necessary to tackle every domain at the same time. Although several existing systems have proved the efficiency of that type of collectors, more detailed tests must be performed. The lack of modeling tools capable of performing holistic simulations is a barrier to research projects in that field. A

great variety of building simulation programs exist but they are, for the most part, specialized in one particular domain and they do not allow a complete analysis. All domains (heating, cooling, ventilation, lighting, and acoustics) are interconnected. Considering that there is no global simulation environment that covers all of the system particularities with the same flexibility, researchers and practitioners must resort to software combination and/or coupling (Citherlet, Clarke, & Hand, 2001). There are four possible strategies:

- *Stand-alone programs*

In this case, a new simulation has to be created for every particular domain of the analyzed system, each time using different software. Thus, this leads to redundancy issues and it can be very fastidious as every time design parameters change in a domain, all the simulations have to be modified and re-run another time. Another constraint for that kind of technique is that the user has to be familiar with all the different programs used.

- *Interoperable programs*

The programs share the same source of information. This can be done following two approaches:

a. Exchange of an entire model or a part of the model
b. Sharing of the model: each program uses information it needs from the common and unique model.

The second approach removes the redundancy but, in any case, the user needs to be familiar with all the programs as well. Although there can be a loss of time dealing with all the different simulating tools, we are closer to the reality of a global project. This strategy clearly represents the interactions between all the actors: engineer, architect, etc.

- *Integrated programs*

In this scenario, several domains are modeled and simulated with the same program. The evolution of the program is simplified as it does not depend on other applications. Moreover it does not need any data exchange format and necessitates only one model grouping all the project information.

- *Coupled programs*

The users have to be familiar with both tools in this case too. Calculations are done simultaneously by two or more programs that also exchange data. Several possibilities of

couplings exist and they will be presented below. This solution offers the best flexibility to the users as it gives them the possibility to benefit from the new functionalities added to the coupled programs.

1.1.3 TRNSYS and ESP-r

Simulating buildings and energy systems in a global approach can be performed efficiently by coupling existing programs specialized in different domains. This requires to choose appropriate programs, not only powerful in their specific domain but also complementary. Two different programs that seem to satisfy these conditions are presented briefly below.

a. TRNSYS

TRNSYS (TRaNsient System Simulation program) is a complete, modular and flexible program for systems simulations (Klein et al., 2010; Keilholz, 2002). The program allows modeling from simple to very complex mechanical plants with varied control systems. The standard libraries contain around 60 components in different domains: HVAC, controls, storage, solar equipment, etc. This list can be completed by additional libraries but also custom-made components that users can create themselves, requiring some Fortran, C or C++ coding skills. TRNSYS is customizable, can be expanded relatively easily, and it can simulate a large number of very specific systems. In addition, it has a user friendly interface for generating projects (Figure 1-1). Components used in the simulation are selected and added to the workspace by a drag-and-drop process before being connected and setup by the user.

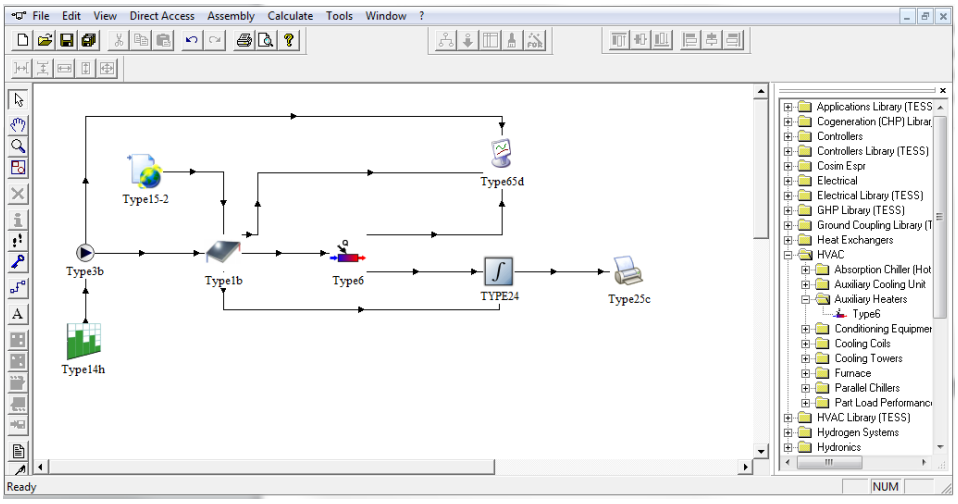


Figure 1-1 TRNSYS Simulation Studio

The simulation environment allows modeling multi-zone buildings. Another possibility of the software is to create, via a specialized editor, redistributable applications. It is particularly intended to develop simplified simulation tools, which can then be freely distributed to users who do not possess a TRNSYS license (Klein et al., 2010).

b. ESP-r

ESP-r is an Open-Source energy modeling program for buildings. Dealing with thermal, acoustic and energy performance, it is a comprehensive integrated energy modeling tool. It helps reducing energy use and emissions, and optimizing the occupant comfort. The source code base can be compiled to run the program on several operating systems: Linux, MacOS, Windows/Cygwin and Windows.

After 30 years of development, ESP-r is a powerful engine (Clarke, 2001) which has proved to be very efficient in the modeling of buildings (Strachan, Kokogiannakis, & Macdonald, 2008). Nonetheless, the program lacks of flexibility when it comes to simulate mechanical systems. This may prevent users from addressing the design of global systems (building + HVAC components). The configuration of controls can be a very complex task. Moreover ESP-r does not have a large list of energy systems components as we can find in other simulation programs such as TRNSYS.

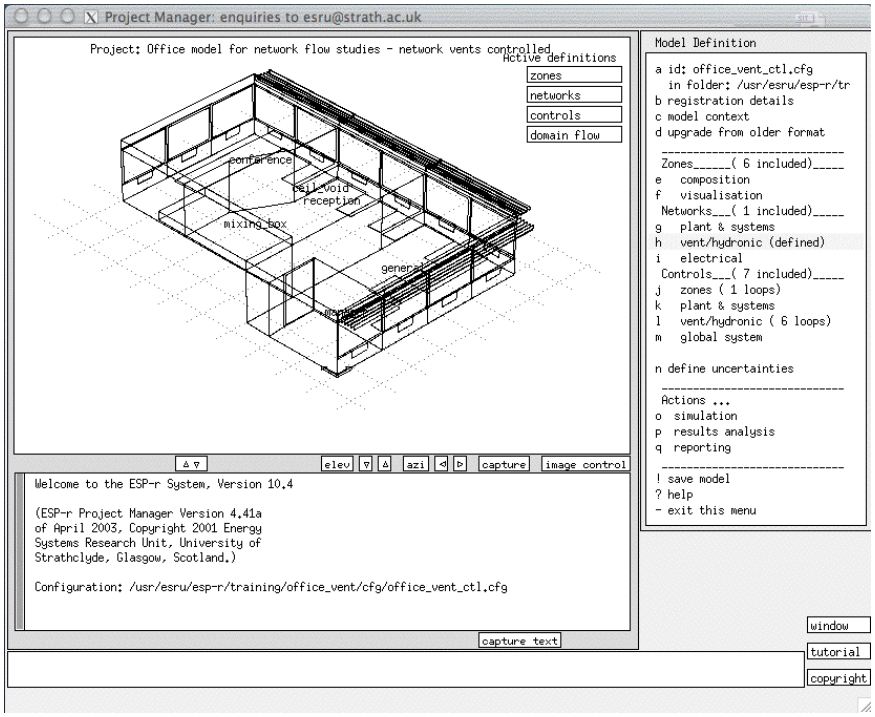


Figure 1-2 ESP-r Project Manager interface

Given the functionalities and specificities of TRNSYS and ESP-r, the flexibility of systems network configuration for the first one and the comprehensive BPS aspects for the second one, a coupling of these complimentary tools would provide results with increased value to those obtained with each individual program.

a. Comparison of ESP-r and TRNSYS

ESP-r and TRNSYS are both tools that allow running dynamic simulations for buildings and energy systems but they have different modeling approaches. Based on a report contrasting the capabilities of several building energy performance simulation programs (Crawley, Hand, Kummert, & Griffith, 2005), a comparison giving a more precise review of the strengths and weaknesses of two programs is presented below.

The most rigorous program in the treatment of the building physics is ESP-r. The program integrates features that are not available in TRNSYS. It uses multi-sided polygons to define constructive elements. It also handles CFD modeling. When it comes to implement very specific types of constructive solutions, ESP-r presents a wide range of materials with models of phase

change materials or transparent insulation. Moreover, ESP-r has the ability to simulate daylighting illumination and controls with its link to Radiance. With all these capabilities, ESP-r possesses more than TRNSYS the comprehensive BPS aspects.

TRNSYS has a larger library of components than ESP-r. This is particularly the case for primary HVAC components (boilers, chillers, etc.). It is also easier for the users to create new components by developing personalized Types and add them to the existing list of components. TRNSYS's modular nature based on components ("Types") also makes it easier to implement specialized control strategies. The ability to develop new components relatively easily and the flexibility offered in combining them into systems and in defining control strategies make TRNSYS well suited to model innovative systems

1.2 Internal coupling

The first option to couple two programs is to combine their source codes. In most of the cases the coupling is done by adding a part of one program code to another. This may be for instance a component modeling a piece of mechanical equipment that we want to model in another environment.

In 1999, Dorer and Weber integrated COMIS source code in TRNSYS. COMIS is a ventilation and contaminants transport simulator for multi zone buildings. This coupling enables to take into account the interaction of air flow rate and transport of contaminants in the modular systems and buildings simulation program. Indoor Air Quality (IAQ) is closely interrelated with thermal comfort and energy performance and must be considered in a holistic design approach. A new component (Type 57) was added to TRNSYS with a re-implementation of the COMIS source code. It is intended to work in combination with the thermal multizone building component (Type 56) and exchange data (e.g. temperature, flow rate) every iteration, similarly to all TRNSYS components connected through their inputs and outputs. While some convergence problems were identified in case of an important stratification of the air in a zone, a study on effects of night cooling on a building proved that the coupling allows new possibilities of simulations and offers a better help to architectural conception (Dorer & Weber, 1999).

On the other hand, some of the existing TRNSYS components in the HVAC and electrical domains have been integrated into other simulation tools. In 1991, Hensen re-implemented a TRNSYS component (known as Type 260) modeling an aquastat controlled heater into ESP-r (Hensen, 1991) The parameters/inputs/outputs structure of TRNSYS components had to be adapted to the ESP-r engine methodologies. More recently, in 2009, a general method to convert components from TRNSYS to ESP-r has been developed (Wang & Beausoleil-Morrison, 2009). The tool, known as the "TRNSYS wrapper", makes it easier to incorporate a TRNSYS Type in ESP-r by compiling the code of the component with the source code of ESP-r. The coupling approach used here is the process model interoperation, since both programs use the same model. A few modifications to the source code are required but they have been minimized as much as possible for this work. For someone who has skills in TRNSYS and ESP-r, creating a new component with the "wrapper" based on the TRNSYS source code should only take a few hours, which is reasonable considering that the solvers of the two programs use very different methodologies. ESP-r solves a global matrix system whereas TRNSYS solve equations sequentially, component by component.

Internal coupling helps to add new capabilities to programs by reusing other programs models, but it requires substantial source code changes. It can only be performed by users knowledgeable in the two programs and in computer programming. Another major drawback of the method is that the source code embedded into the other program is decoupled from the original source code, so that any enhancements or bug fixes will have to be adapted again.

1.3 External coupling

There are different strategies to implement an external data exchange between different simulation programs. The choice can be driven by a variety of factors: the need of a small simulation run time, the accuracy of the results, the amount of modifications to the source code. The most common ways to implement externals couplings based on previous works are presented and discussed below.

1.3.1 The Neutral Model Format

Prior to thinking of how the programs are going to communicate, it is important to define what is going to be exchanged. Indeed, simulation programs often do not use the same format or units for their model data. Software A may calculate energy in Joules while a software B would use Watt-hours. The approach in modeling the same component can be also be completely different. A radiator is for example modeled by a node in a state-space matrix in ESP-r, whereas in TRNSYS it is a black box with a temperature and a flowrate as inputs and calculated flow temperature and power as outputs. In another case we can have two programs simulating two separate aspects of a model as acoustic and thermal effects. The model and its properties are the same for both programs but data needed by each program to do its calculations may differ.

The concept of the Neutral Model Format (NMF) was created in order to simplify the data sharing and compatibility (Nataf, 1995). The file gives all the information that characterizes a system in a generic way. It contains systems of differential and algebraic equations describing the model with a listing of all the variables. The name and description of the model and the variables are also present in the NMF. The objective is to enable the sharing of the model file and exchange of data between several programs. Translators are then in charge of collecting data needed by each program and making the unit conversion if necessary.

The independent format may be more complicated to understand for an experienced programmer, but the advantage of NMF is that it can be read more easily by a large number of programs. More importantly, it allows the programmer to focus on the accuracy of the modeling rather than on writing computer code. Several NMF components such as a solar collector, a multi-layer wall, a thermal zone were created and have proven their efficiency. Vuolle and Bring also proposed a whole library of NMF components regrouping zones, walls, windows and controllers (Vuolle & Bring, 1995). Their work demonstrated that using NMFs reduce the implementation time and improve the efficiency of simulations. Moreover the general model format appears to be a robust and maintainable solution as it is completely separate from the development of the programs.

1.3.2 Sequential coupling

In a paper published in 2005, Djunaedy & Hensen gave an overview of the different possibilities for coupling programs. Unlike internal coupling which is used in order to improve a software program by adding new capabilities, external coupling is relevant when the objective is to share a simulation between two existing programs. It can be the case in modeling different domains in different programs. As shown in Figure 1-3, external couplings can be divided in two categories: sequential couplings and run-time couplings. In the first category, one program is executed after the other. The results obtained with the first program launched are then used in the simulation run with the second program. To improve the precision of the results it can be necessary to repeat the process a few times and use the results obtained with one program in the simulation run with the other one.

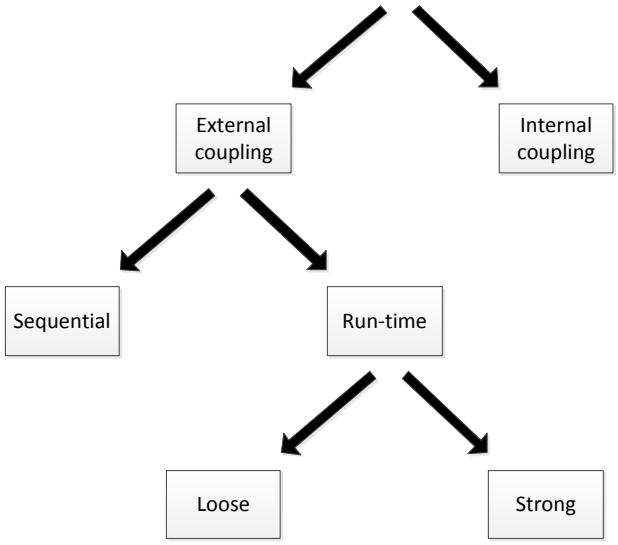


Figure 1-3 Couplings synthesis

The advantage of an external coupling is that the source code of each program is already written, tested and validated. Coupling the programs externally can save substantial time and money in comparison to internal coupling which requires source code changes. This coupling method is easier to maintain as both programs will benefit from bug fixes and enhancements by their own developers.

1.3.3 Run-time coupling

The most complete way to implement an external coupling is to run the programs at the same time and have them communicate during the simulation. This approach is known as run-time coupling. Three possible strategies to implement run-time coupling are shown in Figure 1-4.

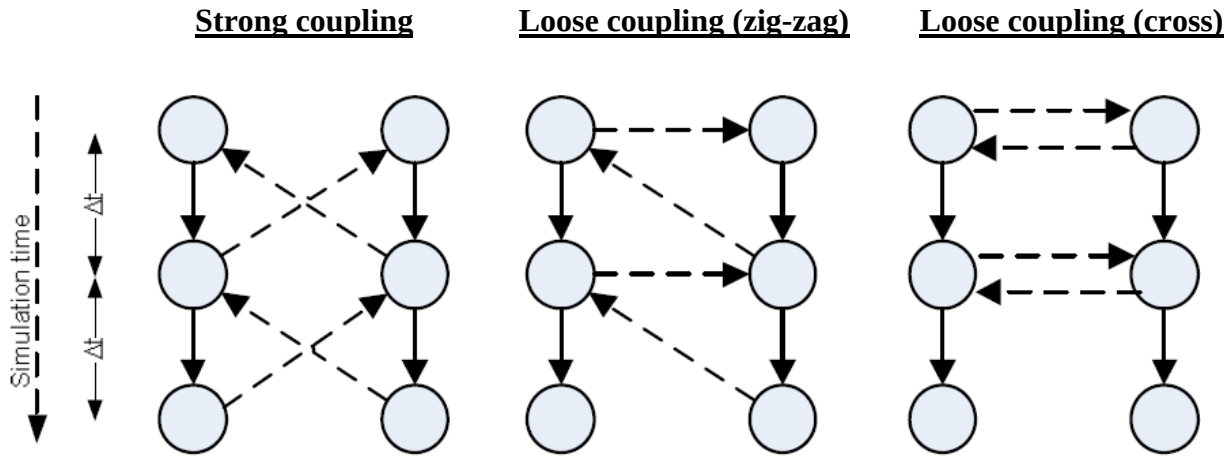


Figure 1-4 Run-time coupling strategies (Trcka, Wetter, & Hensen, 2009)

"The circles represent the subsystem's state at a specific moment in simulation time. The dashed arrows indicate which coupling data (time-step wise) are available to each subsystem before the time-step calculation is performed. The full-line arrows indicate the update of state variables." (Trcka et al., 2009)

- *Loose coupling (zig-zag)*

In loose couplings programs do their own calculations and exchange data only once per time-step. Regarding "zig-zag" coupling (Trcka et al., 2009), one program is executed after the other. E.g.: Program A begins and proceeds with its calculations for the first time-step. Once it has converged, it sends its results to Program B that performs its iterations for the same time-step. In the meantime Program A waits until Program B converges. When Program B is done with its own calculations, it sends data back to Program A which proceeds to the second time-step. The same procedure is executed for each time-step (Δt).

A coupling at the time-step level based on this approach has been made between ESP-r and the lighting simulation program Radiance (Janak, 1999). At each time-step ESP-r calls Radiance and provides it input data. ESP-r waits then until the end of Radiance's iterations, collects the results and uses them in its simulation. Data transfer happens through a temporary text file where the calculated internal illuminance is written by Radiance and read by ESP-r.

- *Loose coupling (cross)*

For that type of coupling the programs exchange data at the end of each time-step. These pieces of information are then used as input data for the following time-step. Each program performs its own calculations on its side and once the two programs have converged, they both send their results to each other. “Cross” and "zig-zag" couplings deliver improved accuracy compared to sequential coupling, because they exchange data at every time-step. In sequential coupling the whole simulation is executed twice, once with one program and another time with the other. In this particular example, the frequency of data exchange is one time per time-step, but it can be extended to decrease the simulation running time. This will depend on the precision of the results wanted (Trcka, 2008).

- *Strong coupling*

In a strong coupling implementation, there are iterations between the two programs at each time-step (Trcka, Hensen, & Wijsman, 2006). The programs exchange data several times per time-step until an overall convergence is reached. Once the whole system has converged the two programs proceed separately to the next time-step and the same "double" procedure of iterations is done until the end of the simulation. This method should deliver a better accuracy at the cost of increased running time, as a higher frequency of the data exchange will result in more iterative simulation calls. This strategy is mentioned in the literature but, according to our literature survey, it has never been actually implemented between two or more complex Building Performance Simulation (BPS) programs.

1.4 Implementation of a run-time coupling

A run-time-coupling is the best solution when existing programs are efficient in a certain domain but not complete enough to be used for a comprehensive energy simulation. This process model cooperation can be implemented in two different ways: the master/slave strategy or the addition of a middleware.

1.4.1 Master/slave strategy

The choice of the co-simulation strategy implies to define which program will have the control of the whole simulation, which program will wait for the other's data, which one is going to impose input data to the other, etc. For the "master and slave" or "base program/external program" approach one program has the control of the other. It is the case for the coupling between ESP-r and Radiance (Janak, 1999) mentioned before where the lighting simulation program is commanded by ESP-r. A coupling of TRNSYS and EnergyPlus realized in 2009 is also based on this subordination relationship between the two programs. Figure 1-5 illustrates the interactions between the two coupled programs and the differences of each program operations sequence for a time-step (Trcka et al., 2009). The "master" program sends data to the "slave" program at the first iteration of the time-step and then waits for the return of data. The "slave" program sends back once it has converged for the time-step. This strategy is particularly adapted to the "zig-zag" coupling coding as one program is executed after the other.

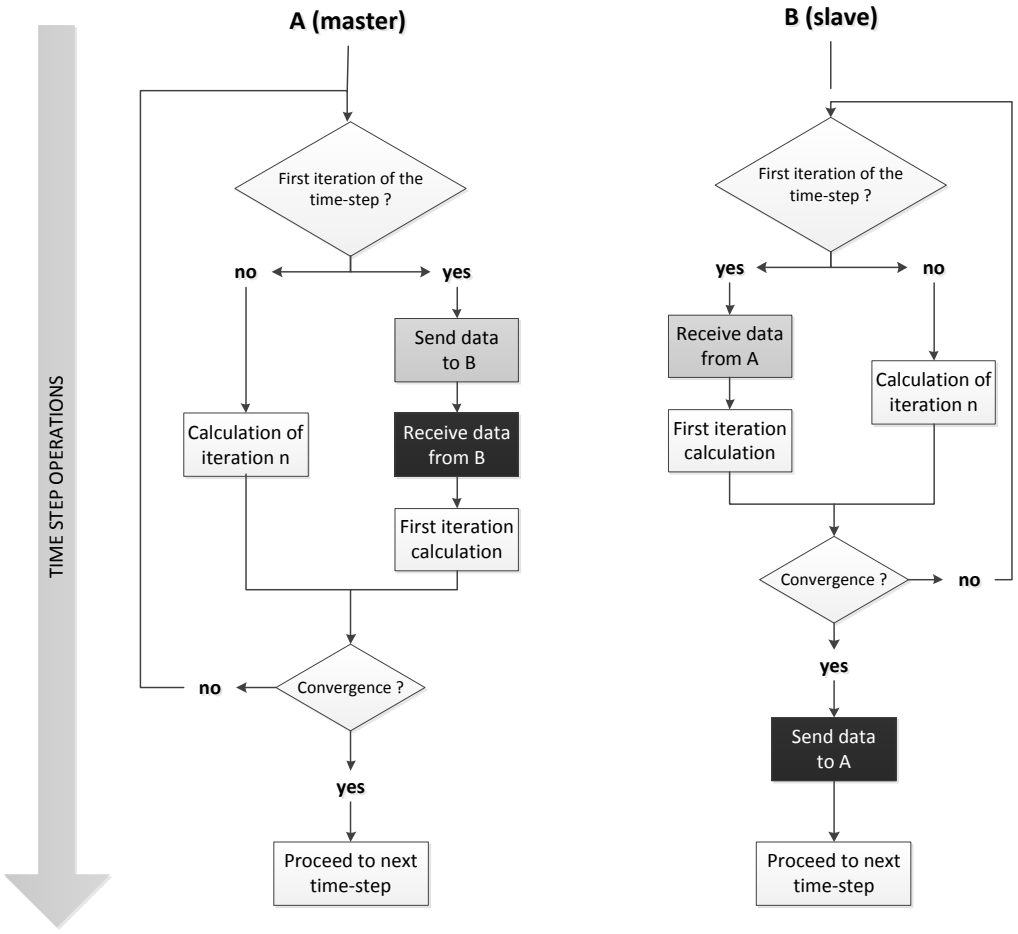


Figure 1-5 Loose coupling zig-zag

1.4.2 Middleware

Another concept of implementation of a run-time coupling that can be found in the literature is the creation of an additional piece of software: the middleware. Also named "mediator" (Gamma, Helm, Johnson, & Vlissides, 1995), its role is to centralize all the communication between the coupled programs. The schematic of *Figure 1-6* presents the interactions between all the programs.

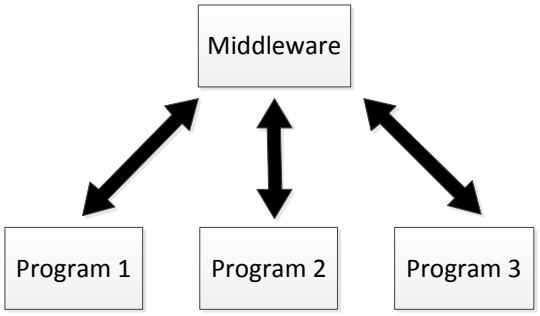


Figure 1-6 Interactions between the middleware and the programs

The middleware simplifies the data transfer handling. Instead of communicating with each other, all programs exchange information with only one program that monitors fluxes of data. It is an efficient way to centralize all the constraints and control functions in the middleware. Gamma et al. (1995) described the simplification of the information exchange by "one to many interaction" instead of "many to many interactions".

An example of the implementation of a middleware in an energy simulation programs coupling is the Building Control Virtual Test Bed (Wetter, 2008, 2011). It is an interface of different simulation tools enabling data exchange. It offers the possibility to link EnergyPlus to other tools and it is therefore meant to be used for testing integrated buildings energy systems and controls. The middleware has its own interface where the user can choose the co-simulation and controls settings. It also has the functionality to analyze the results, print out them graphically and write reports. The coupling approach is based on the "zig-zag" loose coupling concept and there are no iterations between the programs.

CHAPTER 2 ESP-R, TRNSYS AND COUPLING METHODOLOGIES

This chapter includes a review of ESP-r and TRNSYS methodologies and calculation approaches. The main similarities and differences that helped define the guidelines of the coupling implementation will be emphasized. This is followed by a description of the coupling design of the two simulation programs.

2.1 ESP-r methodologies

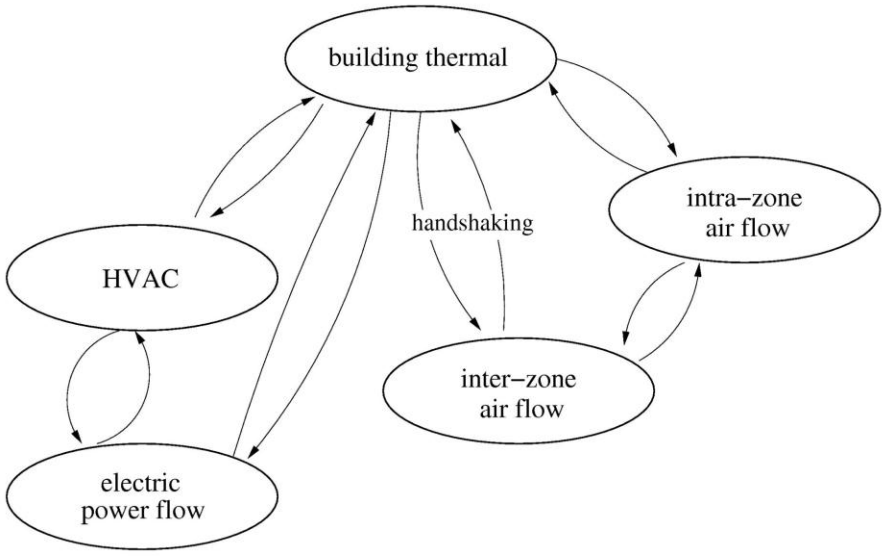


Figure 2-1 ESP-r's partitioned solution approach (Beausoleil-Morrison, 2011)

ESP-r solves the different equations of a simulation using a partitioned solution approach. The problem is solved by discretization in several domains calculated separately. Each domain possesses its own solver that has its own way to solve the equations of the model. The partition into domains as shown in Figure 2-1 includes the building thermal domain, electric power flow, inter zone air flow and intra zone air flow. In order to deal with the relations between the domains and to consider the interdependencies, data is exchanged between the solvers once at every time step. There is an exception for the plant and the electrical domain where iterations can occur within the time step.

2.1.1 Building thermal domain

The building thermal domain is treated with numerical discretization of the model governing equations. The solution is then simultaneously computed by calculating the heat-balances of the whole system. This is essentially done by finding the energy flows with finite difference and control-volume (CV) heat-balances.

Discretization of the model

The first step is the discretization of the entire model into finite differences nodes. As presented in Figure 2-2, nodes represent air volumes of the building, fabric components, interfaces or plants components.

Fabric components include walls, windows, roofs, floors. Depending on their composition and the number of material layers, they may be modeled by several successive nodes.

Interfaces model the behavior of the junction of fabric components and air volumes. They represent properties between a solid and a fluid such as the internal or external faces of walls.

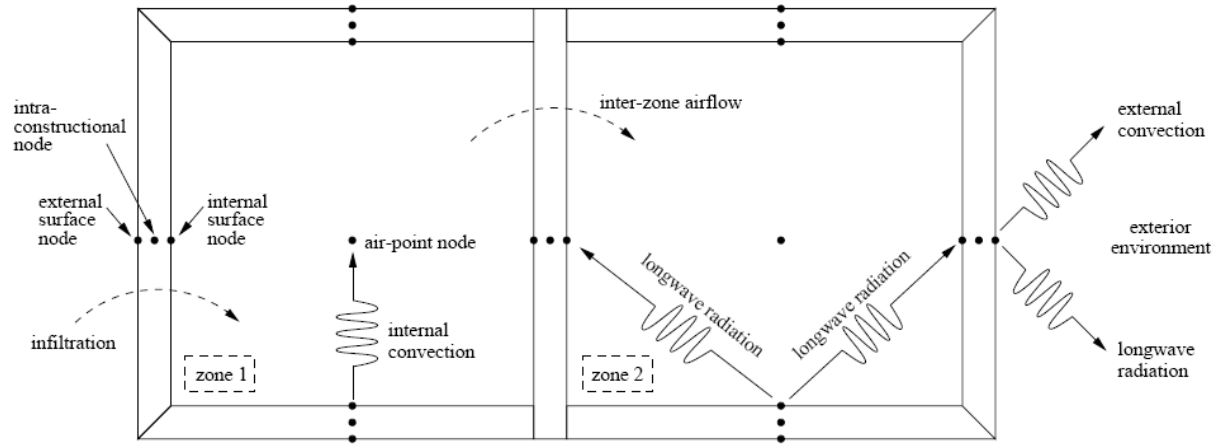
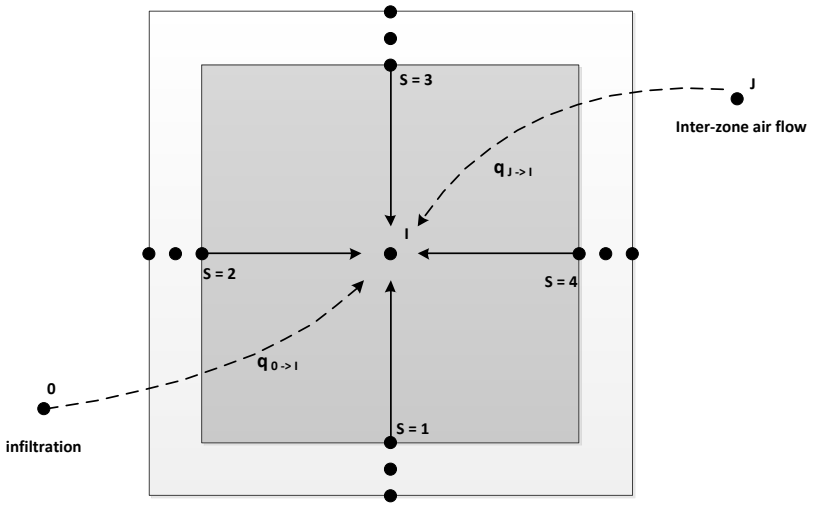


Figure 2-2 ESP-r's building thermal domain finite difference discretization and inter-nodal heat flows (Beausoleil-Morrison, 2011)

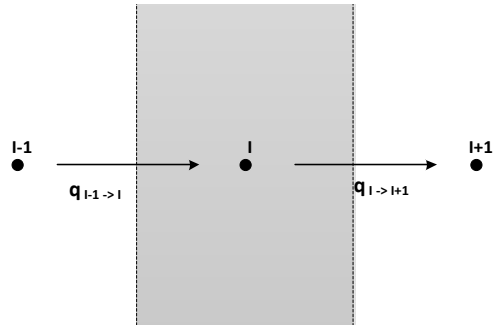
Heat balance solving

The second step is the elaboration of the heat balance for each node. Figure 2-3 and Figure 2-4 show respectively the heat balances with the energy flows implemented for a zone air CV and a node from a fabric component. The amount of thermal energy entering, leaving and created in the node is equated. The equations are then modified and approximated in their algebraic and discrete form.



$$\left\{\begin{matrix}storage\ of\\heat\ in\ CV\end{matrix}\right\} = \left\{\begin{matrix}net\ convection\\into\ CV\end{matrix}\right\} + \left\{\begin{matrix}advection\\into\ CV\ by\\inter-zone\\air\ flow\end{matrix}\right\} + \left\{\begin{matrix}advection\\into\ CV\ by\\infiltration\end{matrix}\right\} + \left\{\begin{matrix}source\ of\ heat\\within\ CV\end{matrix}\right\}$$

Figure 2-3 Heat balance for a zone air CV (Beausoleil-Morrison, 2011)



$$\begin{Bmatrix} storage\ of \\ heat\ in\ CV \end{Bmatrix} = \begin{Bmatrix} net\ conduction \\ into\ CV \end{Bmatrix} + \begin{Bmatrix} source\ of\ heat \\ within\ CV \end{Bmatrix}$$

Figure 2-4 Heat balance for intra-constructional CV (Beausoleil-Morrison, 2011)

Since all nodes are interconnected due to the interdependencies between the components of the building, the pooling of the equations results in an equation set describing the whole system. The solution is finally calculated simultaneously for every node time-step per time-step. At a given time, the resolution of the equations gives the thermal state for each node as well as the heat flows to and from that node.

2.1.2 Plant domain

There are two different possibilities for the user to implement a plant in ESP-r: an ideal plant system or an assembly of selectable components. In both cases the user has to specify how the system is controlled.

Ideal plant

With this configuration, users are able to implement an "ideal" plant system, which will respond exactly to the needs of the building in term of heating and cooling. It does not necessitate detailing all the plant components; only the control of the HVAC system is modeled.

The only indication the user has to enter in the program is how the system is controlled. The variable to control (actuator) and the variable that is sensed by the controller (sensor) have to be specified first. The actuator can be an air point of a zone, a surface, a convective and/or radiative

heater, and/or a location in a fabric component to model the effect of a radiant slab for example. The sensor may be the temperature of one or more zones, external temperature, outdoor wind conditions (speed, direction), the solar radiation (diffuse, direct) or relative humidity. At that point, the control law needs to be specified: heat injection/extraction with fixed capacities, on/off behavior, constant volume with variable temperature, PID controller or free floating without any mechanical heating or cooling.

The ideal plant allows calculating the loads of buildings relatively easily but it may lack precision for detailed simulations as it does not reflect the effects of real components. The response time of a radiator, for example, or the limit to its power output, cannot be taken into account. With this ideal approach the HVAC system is treated with steady-state models

Explicit HVAC

Instead of using the ideal configuration, the user can create the complete network of plant components of the system. A library including tanks, boilers, pumps, heat exchangers, and other mechanical components allows the user to select the needed components for the system he wants to simulate. Their parameters can be modified and for some of them input data is also needed. Components then have to be assembled and in the same way as for the ideal plant, a control strategy needs to be implemented.

Every component is modeled by one or more control volume(s) (CV). A set of mathematical equations representing the behavior of the component are written for each CV. They are used to calculate the energy and the mass exchange between the other connected components and the zone(s). The equations of energy conservation used for all plant components take the following general form:

$$M\ C_p\ \frac{\partial T}{\partial t} = \sum q_i$$

with:

M	the mass of the Control Volume	t	the time
C_p	the heat capacity	q_i	an energy flows
T	the temperature		

Depending on the component, the calculation of the energy flows and generation can be calculated in different ways. Physical (first principle) or empirical approaches may be used. The equations are then solved by a direct solution approach and there are iterations until convergence is reached.

There is a coupling with data exchange between the HVAC domain and the thermal building domain. It allows taking into account the interactions between the two domains. The data transfer is performed both ways once per time step: the building domain is solved at a given time step, calculated temperatures are sent to the HVAC plant domain, which is then solved for that time step. Calculated heat transfer rates from the HVAC plant are then sent back to the building domain which will use them at the next time step. There are no iterations between the two domains within the time step. This coupling between the two domains within ESP-r is a form of "loose zig-zag" according to the nomenclature described above.

2.1.3 Electrical domain

The electrical domain is treated as a network of electrical components and nodes. The components may be cables, transformers, inverters, etc. The nodes are used to calculate the electrical variables: voltages, currents and power. A Newton-Raphson based solver is used to solve the electrical energy balances for all the nodes.

The electrical domain can be coupled to other domains as the HVAC, e.g. in the case of a mechanical component producing or consuming electricity (pump, electric heater, co-generation device).

2.2 TRNSYS methodologies

TRNSYS solving methodologies are different from those implemented in ESP-r. Whereas ESP-r uses more a global approach and calculates a general solution within each domain and then implements a loose coupling between the domains, TRNSYS separates the problem and solves it one component at a time, then performing overall system iterations until all components (and therefore all domains) converge simultaneously.

2.2.1 Overview

The TRNSYS software suite includes 3 different interfaces: the Simulation Studio, TRNBuild and TRNEdit.

Simulation Studio

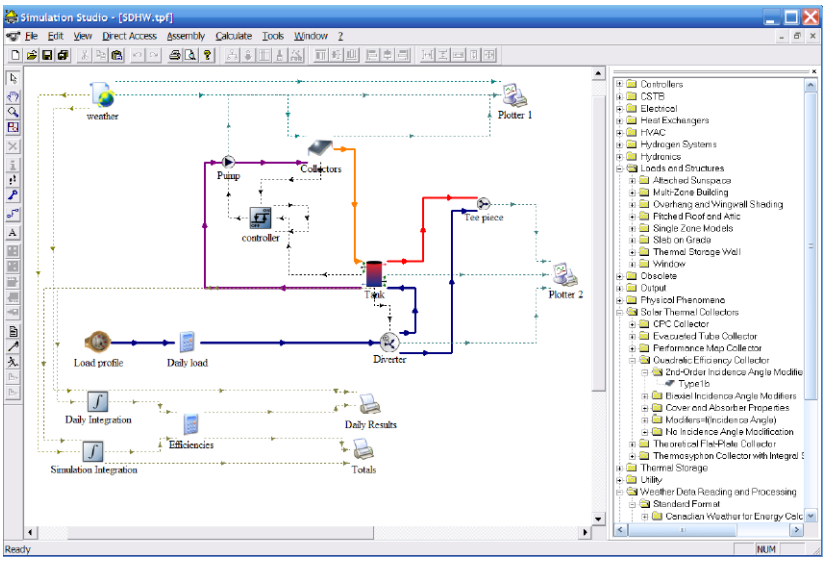


Figure 2-5 Simulation Studio

The simulation studio is the main TRNSYS interface. It generates the simulation project files. This is where all the components of the mechanical system are assembled into a complete model. The components, known as TRNSYS "Types", are linked together and form the system network. The Simulation Studio executable allows modifying the simulation settings as the simulation running time, the length of time steps and convergence criteria. When the system is configured and simulation parameters are set, the TRNSYS input file (a text file known as the "deck" file) can be created and the simulation launched directly from the Simulation Studio. In the TRNSYS jargon, each instance of a Type, i.e. each component in the assembled simulation, is called a "Unit". So each component icon in Figure 2-5 corresponds to a Unit.

TRNBuild

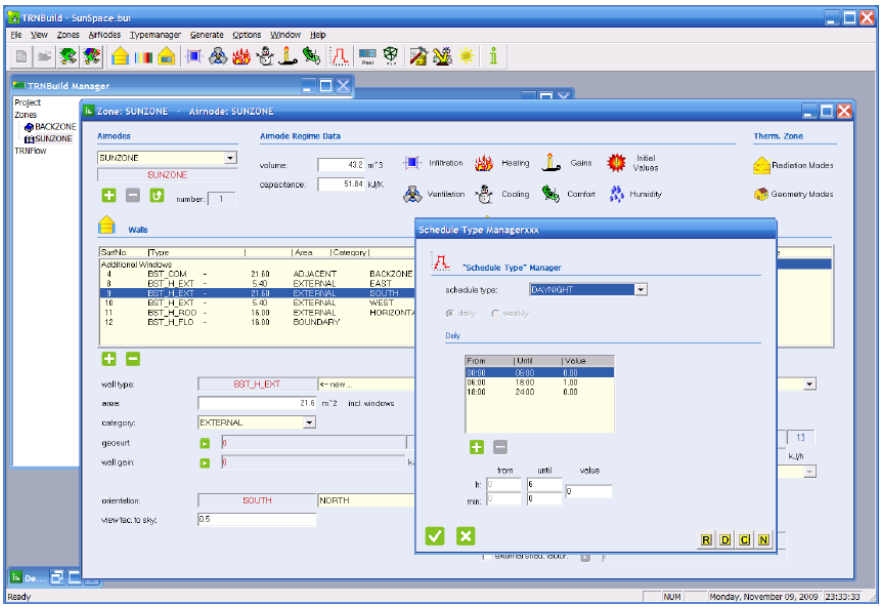


Figure 2-6 TRNBuild

This interface is used to define multi-zone building models. Here, all the characteristics of buildings as material, zones, ventilation, loads, etc. can be defined. The interface is dedicated to configuring parameters for the multi-zone building model in TRNSYS, known as Type 56. The configuration and the properties of the building are saved in text files written by TRNBuild, which are then read by Type 56 during a simulation. Version 17 introduced a link between TRNBuild and Google Sketchup through a plugin known as TRNSYS 3D. This plugin enables to define the geometry of the building and the different zones by drawing them in Sketchup instead of entering their description in TRNBuild. The Sketchup drawing is translated by the plugin and imported into TRNBuild where non-geometrical characteristics (e.g. schedules) can be defined.

TRNEdit

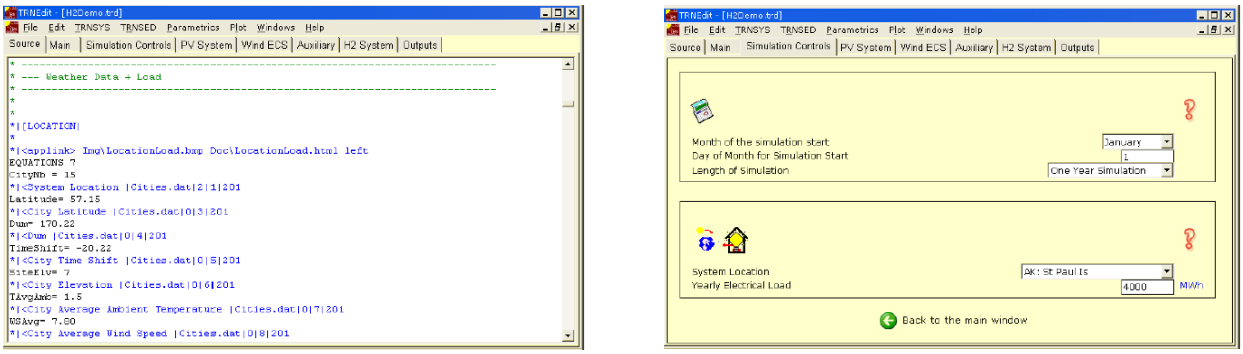


Figure 2-7 TRNEdit interface and example of a TRNSED application

The TRNEdit interface allows to edit the TRNSYS input file (“deck” file). This can be useful to perform parametric runs that are not supported by the Simulation Studio or to create stand-alone redistributable programs with their own simplified interface. These stand-alone executables are called TRNSED applications. They offer the possibility to users that do not have a TRNSYS license to simulate some predefined energy systems. The main restriction of these applications is that users can only change selected simulation parameters accessible from pull-down menus or text boxes. They do not have access to an interface to reconfigure a simulation such as the Simulation Studio.

2.2.2 TRNSYS Types

The Types are all the components used in a TRNSYS simulation. They are characterized by 3 categories of variables. The parameters are defined once by the user and remain constant over time. The inputs and outputs represent data that can be exchanged with other components from the simulation. The value of a Type input can be the output of another component when they are connected together. If an input is not connected it will keep its initial value specified by the user. Outputs are the results of the Type calculations. Some other components may need these results as an input variable so a connection can be made between the Types. For each Type, an input can have only one connection with the output of another Type but an output of a Type can be connected with one or more inputs of other Types. An illustration of the creation of a Types network is proposed in Figure 2-8.

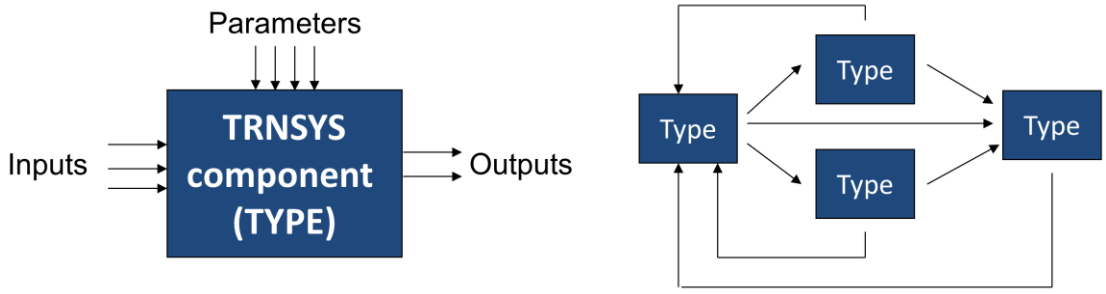


Figure 2-8 TRNSYS Type and network topology

There is a large variety in the nature of Types. They do not only represent mechanical components but also a large choice of so-called utility components that do not represent actual equipment but are useful to the simulation (e.g. weather data readers). The main groups of components are listed below:

- **Mechanical and electrical components**

  They are the standard and most used components. They represent real components as a stratified storage tank, a solar collector, a heat exchanger, etc.

- **Controllers**

  These components are used to set the control strategy of the system. Thermostats, differential controllers, PIDs are for example included in the controllers library.

- **Building and loads**

  They include different building models, from degree-day analysis to detaile multi-zone building, but also components applying pre-calculated loads to a flowstream.

- **Outputs**

  Components of this group define the output files of the simulation. What results should be written to a file (“printed” in TRNSYS jargon), plotted, integrated; the period and the frequency of the results can be specified with these components.

- **External file readers**

  They include the components that are specifically used to read data from external files. The most frequently used Type from this group is the weather data reader and processer, but generic data readers can be used to read any text file (e.g. schedules or pre-calculated loads).

- **Utility**

  All other manipulations, operations on data can be handled by this group of Types. They also include Types exchanging data with other programs as EES, Matlab, Comis, etc.

The flexibility of the TRNSYS structure enables users to add their own Types to the standard library of components, largely coded in Fortran. However, any programming languages that are compatible with the Microsoft Windows shared libraries structure (Dynamic-Link Library, or DLL) can be used, e.g. C++

2.2.3 Solver

The TRNSYS engine has a structure of shared libraries also called Dynamic-Link Libraries (DLL). When the TRNSYS executable, "TRNExe.exe", is launched (generally by the Simulation Studio), it reads the simulation input file, the "deck file", and calls the TRNSYS main DLL, "TRNDll.dll". The process is presented in Figure 2-9.

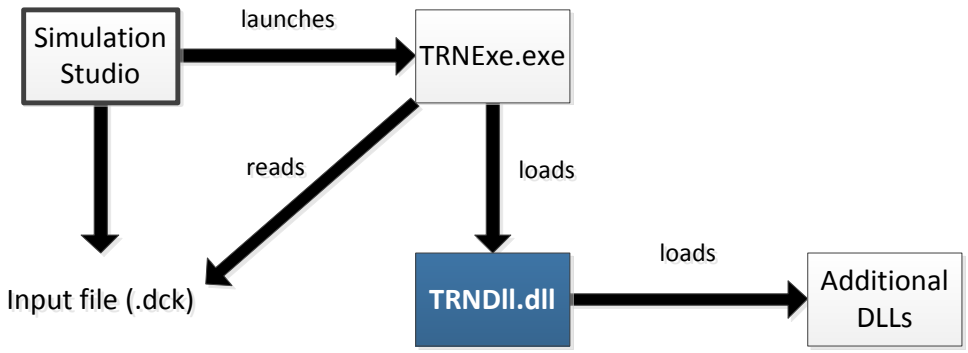


Figure 2-9 Interactions between the main TRNSYS programs and files during a simulation

TRNDll.dll contains the source code of TRNSYS. It contains two parts: the kernel (solver routines) and the Types (TRNSYS components). Some components such as user-written Types or Types from commercially available additional libraries do not have their code compiled in the

main DLL. They are compiled into additional DLLs that are loaded by the main DLL (TRNDll) as required.

TRNSYS implements two different solvers. Only the default solver, known as "solver 0" (successive substitution) is discussed in this document. During a simulation, Types subroutines are called one at a time by the kernel. Information from some Types' outputs is passed to the inputs of connected Types. For the kernel, each component is treated as a black-box and it does not make any assumption on what the Types calculate and what is the nature of their inputs and outputs. Figure 2-10 shows the relations between the kernel and the Types. As the components exchange data, more than one iteration may be needed at each time step. Every Type is called at least once at the beginning of a time step and additional calls are performed by the solver as required. Convergence is checked on the variation of the input values of each Type. Types whose inputs have changed more than a given tolerance compared to a previous iteration are called again. This is repeated until the change between the values of two successive iterations is lower than the specified tolerance. Types that do not have been called at some iteration because their inputs did not changed are not blocked and can be called again if their inputs change in future iterations. When all Types have converged TRNSYS proceeds to the next time step.

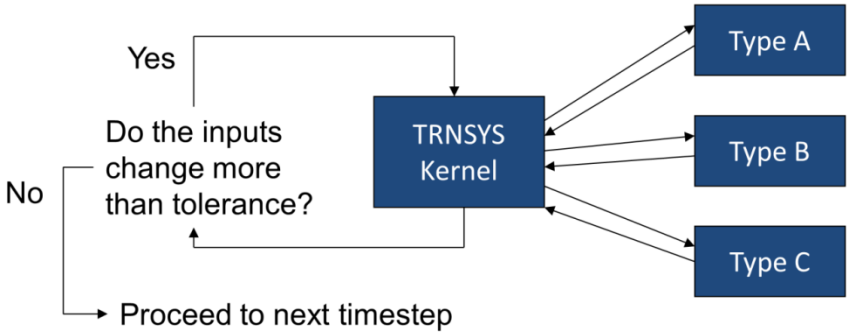


Figure 2-10 TRNSYS solution methodology

A maximal number of iteration per component at each time step is defined by the user to prevent infinite loops when the solver does not converge. If this number is reached, the kernel proceeds to the next time step but writes a "warning" message indicating that a component did not converge at a certain time. Excessive non-convergence warnings will trigger an error message and stop the simulation.

2.2.4 Categories of Types

Previously, we saw that the nature of the Types can be very different. Some of them are standard mechanical components that must be called as soon as time has been incremented or their inputs have changed. Other components such as data readers or printers should only be called at the beginning or at the end of a given time step. Different categories of Types are defined in TRNSYS to describe the timing and frequency of their calls during the simulation. Figure 2-11 represents the sequence of calls to the different categories of Types (category numbers do not follow a logical order for historical reasons).

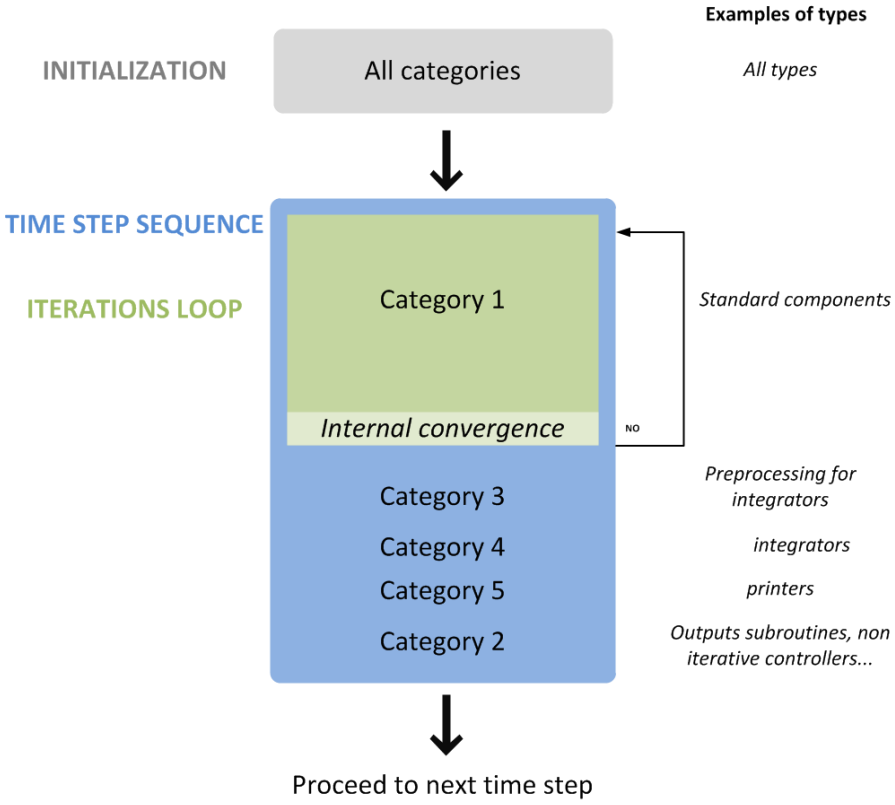


Figure 2-11 Sequence of calls to the different categories of Types

In total there are 5 categories of Types listed below:

Table 2-1 Categories of Types

Category 1	*Standard components*	They are called at every iteration when their inputs have changed
Category 3	*Pre-processing for integrator*	Called right after the standard types convergence, they perform the calculations necessary for the integrators
Category 4	*Integrators*	They integrate data coming from their inputs
Category 5	*Printers*	Data connected to their inputs is written to an external file
Category 2	*Outputs components.*	Last Types to be called

2.3 Co-simulation approach

After studying the methodologies of the two programs, it was decided to implement a strong run-time coupling under the control of a middleware. The objectives and the methodology of the coupling are detailed in the following paragraphs.

2.3.1 Run time coupling

TRNSYS only supports Microsoft Windows, so that Operating System (OS) was selected for the run-time coupling. For practical reasons the parallel execution of the two programs is limited to a single computer. These initial decisions helped to define the implementation of the coupling.

Strong coupling

An original contribution of this work was the implementation of a strong run time coupling. Not only the programs run together step by step and exchange data, but they iterate together at the time-step level. Schematics from Figure 2-12 show the differences between strong coupling and other types of run-time couplings. The squares represent time-step calculations for one program and the arrows illustrate data transfer.

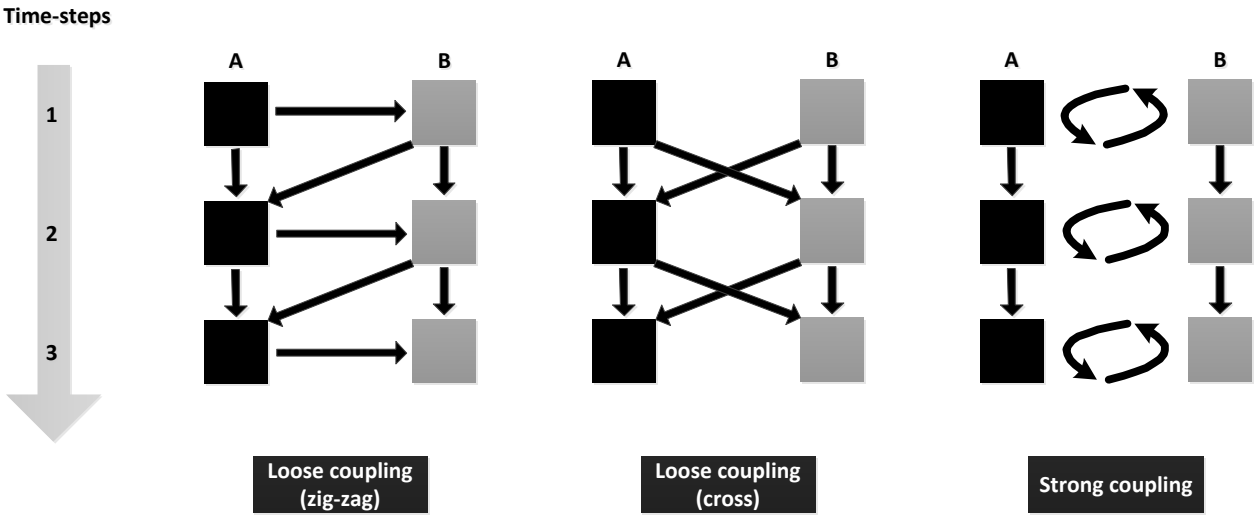


Figure 2-12 Differences in run-time couplings

In the first two cases, the two programs are executed one after each other and exchange data in both directions once per time-step. In the case of strong coupling, data are exchanged several times per time step as there are iterations between the two programs. There are two levels of convergence in this case. The first convergence is internal to each program and is the same as when they are executed separately. The second one concerns the overall convergence of the co-simulation.

Because of the coupling structure involving two internal iteration loops within a global iteration loop, the simulation run time can be expected to be longer than in a loose coupling. One method to alleviate this problem is to run the two programs in parallel (instead of sequentially) when they do not exchange information. This can be realized by running the two programs in their own thread.

Processes vs. threads

As it was decided that the two programs would run simultaneously and not sequentially, there are two possibilities of implementation. The two programs can run as separate processes or as a multiple threads included in a single process. A process is an independent execution unit that contains its own state information and its own address space. A thread is a single sequence of instruction executed within a process, which has processor time allocated by the OS. The multi-processes option enables data sharing but not at the same time and it needs the OS for

synchronization. As efficiencies of the two options are similar (Schmidt & Huston, 2002) it was decided to run the two programs with separate threads in order to minimize the run time.

2.3.2 Middleware

A middleware was created to supervise the exchange of information between the two programs, as implemented within the BCVTB (Wetter, 2008, 2011). The idea behind this concept of coupling design is to minimize changes to the existing programs. This will deliver a solution that should be easier to maintain: parallel development of TRNSYS and ESP-r can continue without any impact on the coupling method as long as the routines and data structures used to communicate with the middleware are not modified. The middleware specifically developed by the design team for this project is known as the "Harmonizer". It includes an executable (called the Harmonizer launcher) and another compiled DLL (the Harmonizer DLL) communicating with the ESP-r and TRNSYS DLLs. This configuration allows the Harmonizer to have access to the subroutines of TRNSYS and ESP-r.

The role of the Harmonizer is to control the coupling, determine the convergence, manage the marching through time of the two programs, and ensure the synchronization of the data exchange. As shown in Figure 2-13, all information exchange passes through the harmonizer. There are no direct data transfer between TRNSYS and ESP-r.

Figure 2-13 Data flows between the Harmonizer and the coupled programs

The different functionalities of the Harmonizer are presented below:

1. *Initialization of ESP-r and TRNSYS*

   At the very beginning of a simulation the Harmonizer loads the DLLs of the two programs. The middleware is also in charge of checking that the simulation parameters (time step and simulation periods) from both programs input files are the same.

2. *Launching of the simulations*

   The harmonizer starts the simulations of the two programs. ESP-r is the first program that begins with the building thermal and the plant domains. TRNSYS is then launched and ESP-r finishes with the electrical domain.

3. *Monitoring the data transfer*

   Results from the building thermal and plant domains are collected by the Harmonizer and then transmitted to TRNSYS. In the same way, once TRNSYS has converged data is sent back to ESP-r via the Harmonizer.

4. *Checking the convergence*

   The internal convergence of each program is watched by the Harmonizer. When the two programs have converged, the Harmonizer checks the data exchanged and decides if there is overall convergence. This occurs when the difference between data coming from each program at successive iterations is smaller than a determined tolerance.

5. *Controlling the marching forward through time*

   Once overall convergence is reached, the Harmonizer tells each program to continue and proceed to the next time step.

More details about the design of the Harmonizer can be found in the paper written by the Design Team (Beausoleil-Morrison et al., 2011).

2.3.3 Exchange of data

The coupling was specifically designed to run co-simulations with buildings modeled in ESP-r and mechanical system in TRNSYS. However the way it is implemented allows more mixed couplings with some plant components implemented in ESP-r, for instance. In any case, the

terminal device of the system (e.g. radiator, supply air or radiant floor) must be treated in ESP-r. The nature of exchanged variables was chosen in order to maximize modeling flexibility.

Variables that are exchanged are grouped into a derived data structure (DDS) shared between the Harmonizer and both simulation programs. This solution appeared to be easier to handle than an array made of different data. It facilitates the transfer, but also to store and retrieve data as it is classified by type of information within the DDS as presented in Figure 2-14.

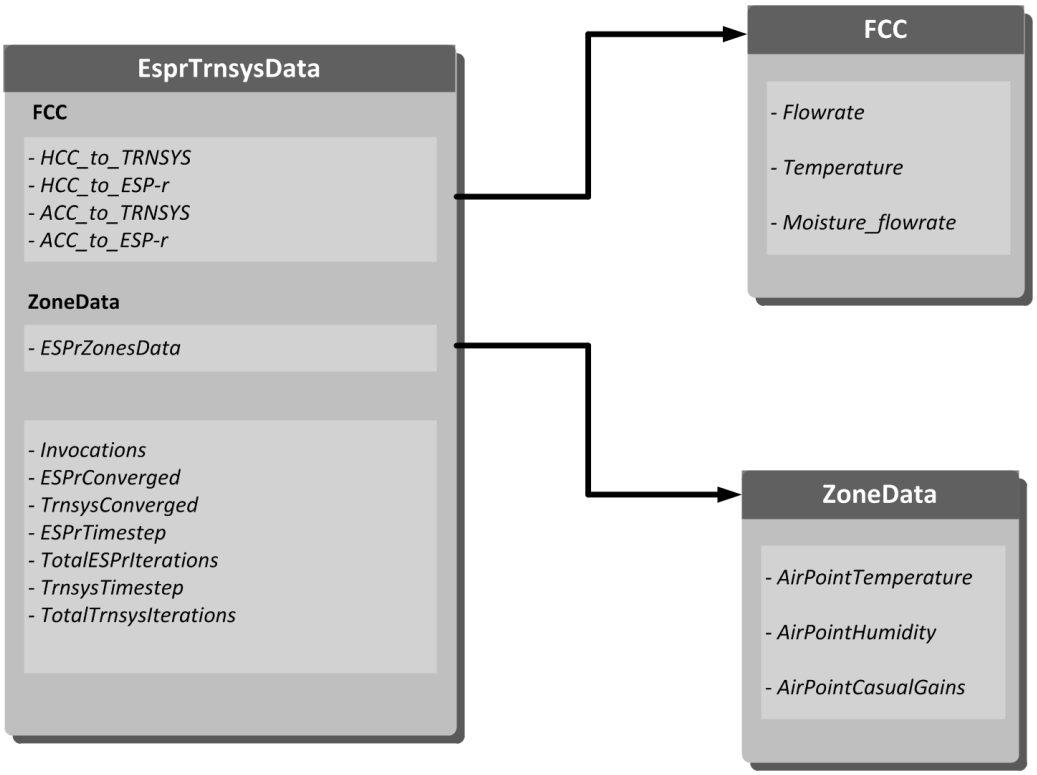


Figure 2-14 Derived Data Structure

The DDS is composed of 3 main categories of variables: data indicating the state of a fluid that is transferred from a program to the other (flow rate, temperature, humidity), the state of the air of a zone (temperature, humidity, casual gains) and checking data informing the Harmonizer where the 2 programs are in the simulation (number of invocations, time steps, iterations).

The different variables and types are described in the following array:

Table 2-2 List of variables and types from the derived data structure (part 1)

Name	Nature	Description	Units
EsprTrnsysData	type	Main type containing all the data	/
HCC_to_TRNSYS	type	Type containing water flow data from ESP-r to be sent to TRNSYS	/
HCC_to_ESP-r	type	Type containing water flow data from TRNSYS to be sent to ESP-r	/
ACC_to_TRNSYS	type	Type containing air flow variables data ESP-r to be sent to TRNSYS	/
ACC_to_ESP-r	type	Type containing air flow data from TRNSYS to be sent to ESP-r	/
ESPrZonesData	type	Type containing zones data	/
Invocations	integer	Number of times the Harmonizer called the two programs per time step	/
ESPrConverged	integer	Flag of convergence for ESP-r (equal to 1 if ESP-r has converged and 0 if not)	/
TRNSYSConverged	integer	Flag of convergence for TRNSYS (equal to 1 if TRNSYS has converged and 0 if not)	/
ESPrTimestep	integer	Number of the ongoing ESP-r time step	/
TotalESPrIterations	integer	Total number of ESP-r iterations since the beginning of the simulation	/
TrnsysTimestep	integer	Number of the ongoing TRNSYS time step	/
TotalTrnsysIterations	integer	Total number of TRNSYS iterations since the beginning of the simulation	/

Table 2-3 List of variables and types from the derived data structure (part 2)

FCC	type	Type containing fluid flow data	/
Flowrate	double	Mass flow rate of liquid (HCC) or dry air (ACC)	kg/s
Temperature	double	Temperature of the fluid	°C
Moisture_flowrate	double	Water mass flow rate (ACC only)	kg/s
ZoneData	type	Type containing zone data	/
AirPointCasualGains	double	Thermal losses from mechanical components injected in the zone	W
AirPointHumidity	double	Humidity ratio of the zone	/
AirPointTemperature	double	Temperature of the zone	°C

2.3.4 Harmonizer functions

TRNSYS and ESP-r exchange data included in the shared structure through the Harmonizer. To pass and get data from the other program they call functions in the Harmonizer. Two of them are called by ESP-r to pass data to TRNSYS (PassDataToTRNSYS) and collect data from TRNSYS (GetTrnsysData). It is the same on the TRNSYS side with the functions “PassDataToEspr” and “GetEsprData”.

Another function (GetSystemConv) is called by each program to know if the other program has converged and if the overall convergence has been reached. A flag returned by the Harmonizer to each program authorizes it to proceed to the next time step. The order of the calls to these functions is essential to ensure the good synchronization of the system.

Figure 2-15 represents all the data exchanges and Harmonizer actions during a co-simulation. The progress of a co-simulation can be summarized in 8 steps :

1. *Initialization of ESP-r and TRNSYS*
   The Harmonizer loads the DLLS of the two software.

2. *Creation of ESP-r thread*

   The Harmonizer gives ESP-r the signal to start the simulation.

3. *ESP-r building and plant domains calculations*

   ESP-r begin its own calculations for the building thermal and the plant domains.

4. *Data sent from ESP-r to TRNSYS*

   Once the building and the plant domains have converged, ESP-r calls "PassDataToTrnsys" and sends the results to the Harmonizer. TRNSYS calls on his side "GetEsprData" to collect the data.

5. *TRNSYS iterations*

   TRNSYS performs its own calculations with the data collected from ESP-r.

6. *Data sent from TRNSYS to ESP-r*

   Once the TRNSYS solver has converged, it calls "PassDataToEspr". The Harmonizer collects the data coming from TRNSYS and passes it to ESP-r by calling the function "GetTrnsysData".

7. *Overall checking convergence*

   The Harmonizer checks the convergence of the two programs separately as well as the overall convergence of the system. Both TRNSYS and ESP-r call "GetSystemConv" in order to know if overall convergence has been reached. If not steps 3 to 6 are repeated.

8. *ESP-r electrical domain calculations*

   The Harmonizer has given the signal that there is overall convergence. ESP-r continues with the calculations of the electrical domain and then proceeds to the next time step. Nothing more is done on the TRNSYS side. It proceeds immediately to the next time step.

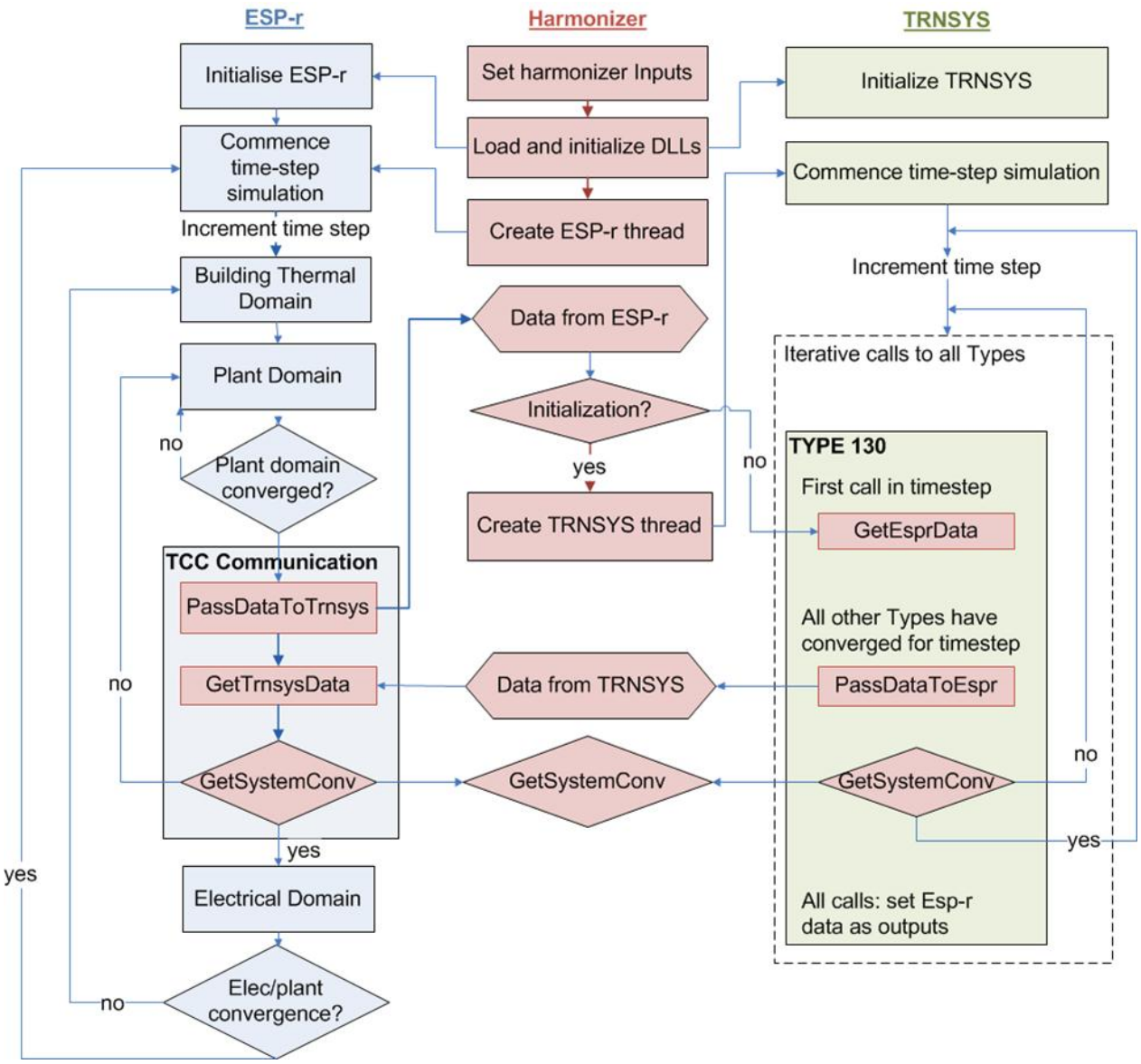


Figure 2-15 Interactions between the two programs and the Harmonizer (Macdonald, 2012)

CHAPTER 3 SOURCE CODE MODIFICATIONS

This chapter presents all the additions and modifications to ESP-r and TRNSYS source codes that have been implemented to enable co-simulation.

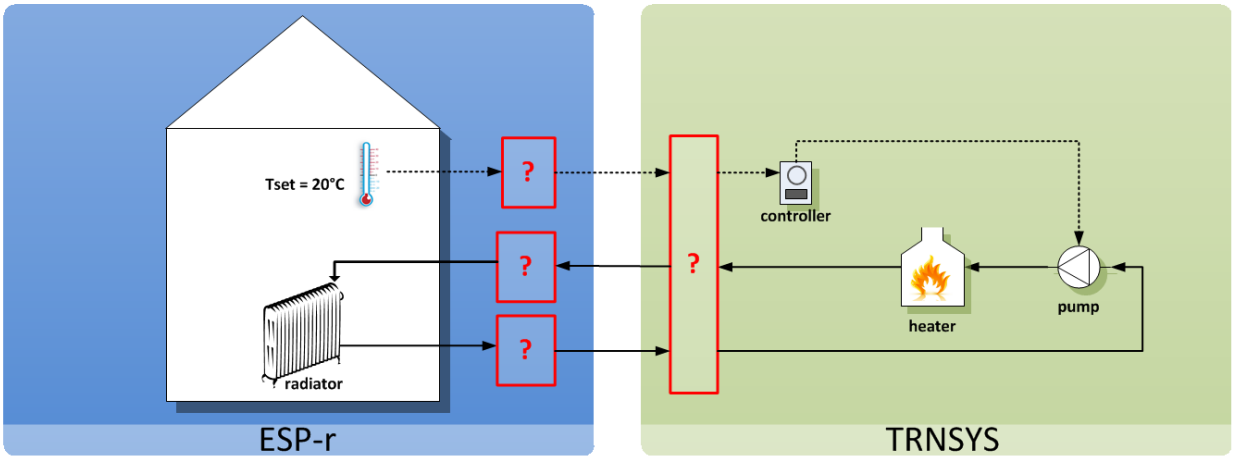


Figure 3-1 Coupling components strategy to transfer data to the other program

As presented in Figure 3-1, the strategy of exchanging data consists on the creation of coupling components in both programs. We will see now how they work and how they are integrated in the existing source codes.

3.1 Modifications in ESP-r source code

Modifications to ESP-r include the addition of new components and a new subroutine. These changes will be discussed briefly as this is out of scope of this master thesis, the work being performed by the Carleton University team.

3.1.1 Coupling components

New components were added to the ESP-r plant domain to pass and receive data from a TRNSYS network. Called the TRNSYS Coupling Components (TCC) their role is to exchange information of a fluid flow with the Harmonizer.

There are two types of these coupling components depending on the nature of the fluid (air or liquid) that is passed from one program to the other:

- Hydronic Coupling Components (HCC)
- Air-based Coupling Components (ACC)

Data exchanged between the Harmonizer and a HCC or an ACC are not the same. In the case of a HCC the temperature of the fluid and the fluid mass flow rate is transferred. Temperature of the air, dry air flow rate and moisture flow rate are exchanged when it comes to an ACC.

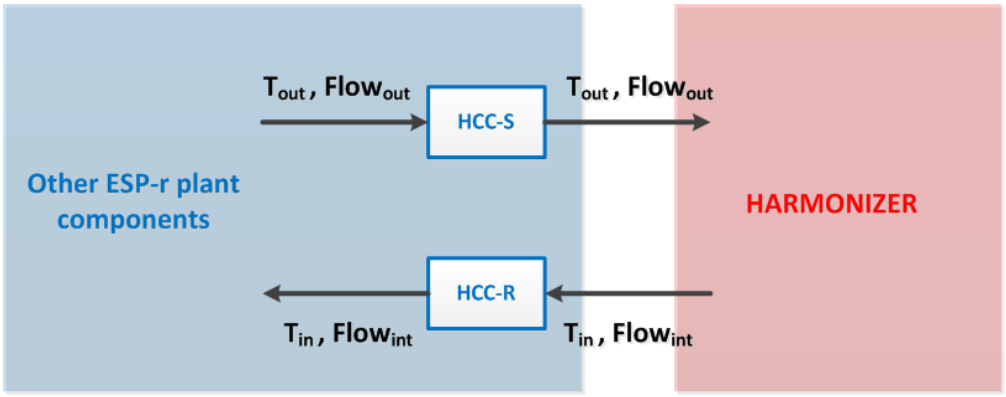


Figure 3-2 TRNSYS Coupling Components

As shown in Figure 3-2 with the example of HCCs, each component can be “sending” or “receiving”. The same distinction is made for the ACCs. A sending component collects fluid flow information from another component in ESP-r and transmits the data to the Harmonizer. A receiving component does the opposite. It passes data coming from the Harmonizer to a component of the plant domain.

From the users perspective, adding and configuring a TRNSYS coupling component is performed the same way as for traditional plant components. The user has to be in the explicit HVAC mode, then choose the type of coupling component (HCC or ACC, receiving or sending) from the library, add it to the plant network and connect it to the other components of the simulation.

3.1.2 Coupling subroutine

In addition to the transfer of variables representing real fluid flows from mechanical components it is also essential to exchange information regarding zones. The temperature of the zone is for example required for TRNSYS to perform the control of heating or cooling systems. A new subroutine, "TCC_communication", was coded in ESP-r. It handles exchange of data between the Harmonizer and the ESP-r thermal building domains. Air-point temperatures and absolute humidity are passed automatically by the subroutine to the Harmonizer.

In addition to that, TCC_communication collects casual gains from TRNSYS components and injects them to the zones. If we consider an example of a stratified storage tank located in a basement. Heat losses from the water stored in the tank depend on the temperature of the basement. Assuming that the storage tank is modeled in TRNSYS and the basement in ESP-r, TRNSYS needs to know the surrounding temperature to calculate the temperature of the stored water. On the other hand, the temperature of the zone depends on the thermal losses of the tank. So thermal losses have to be injected to the zone and therefore passed to ESP-r.

3.2 TRNSYS: Creation of a new category of Types

On the TRNSYS side, the communication with ESP-r is made with one single component. This new Type is capable to exchange data with the Harmonizer but it can also intervene on the TRNSYS solver iterations management. TRNSYS source code were implemented by the author of this Master's thesis with inputs from the Design Team.

3.2.1 Objectives

The main objective of source code changes was to minimize modifications to TRNSYS kernel routines. This had the advantage of saving development time and to improve the maintainability of the changes. Fewer modifications to main kernel routines means a lower probability that future developments in TRNSYS will have an impact on the coupling process.

The easiest way to add new features to TRNSYS is the addition of new Types, as it is done in practice by many TRNSYS users when they develop their own components. Adding a new Type consists in writing a new subroutine and compiling it as a DLL (or adding it to the main DLL, TRNDll). The new component must comply with a calling structure documented in the TRNSYS programmer's guide (Klein et al., 2010) and use certain access functions to interact with the solver. It was decided that the exchange of data with ESP-r through the Harmonizer would be implemented through a specific Type, which was assigned number 130. This new component is consequently known as Type 130, and it was released officially with TRNSYS version 17.01.25

3.2.2 Data exchanger Types

The new communication Type handles data exchange between the two programs but also the task of managing iteration and informing the TRNSYS solver about overall (co-simulation) convergence. Indeed, the strong coupling approach requires that TRNSYS be forced to continue iterating and calling for new data from ESP-r even after its own convergence at a particular time step, as long as overall convergence has not been reached. The Type has different roles depending on the state of TRNSYS internal convergence:

- If TRNSYS has not yet converged for a given time step, the routine should allow TRNSYS to finish its iterations without communicating with the Harmonizer.
- If TRNSYS has converged the Type should call the middleware to know if the whole co-simulation has converged too. If it is the case TRNSYS should be allowed to proceed to the next time step. If not, new data have to be exchanged with ESP-r and TRNSYS needs to execute more iterations for the same time step.

The capability for a TRNSYS Type to interact with the kernel and prevent it from declaring convergence and proceeding to the next time step did not exist in TRNSYS prior to this work. Furthermore, the capabilities required by the Types functions that we wanted to implement were not adapted to any of the existing Type categories presented in section 2.2.4. Indeed, the communication Type needs to be called as a classical component from Category 1 to provide data coming from ESP-r to the other Types of the simulation. It also needs to collect data from other Types and pass it back to ESP-r. In addition to that, an extra call to this Type is necessary for the overall convergence checking and TRNSYS iterations control.

A new category of Types was created to handle the calls to the data exchanger component. Types from this category are called in the same time as standard components from the first category and work in the same way at this time. This allows the Type to be integrated in a TRNSYS network and exchange data with other Types within the normal information flow. For other components, this Type will act as standard TRNSYS Type passing variables to and receiving variables from other Types. An additional call to this Type is performed right after the internal convergence of TRNSYS and just before the “end-of-time step” call to all TRNSYS components that takes place once convergence has been detected by the solver. During that call, Type 130 tells the kernel either to proceed to post convergence calls and to the next time step or to continue iterating, if overall (co-simulation) convergence has not been reached. The schematic of Figure 3-3 shows at which time components from the new category of Types will be called in the calling sequence.

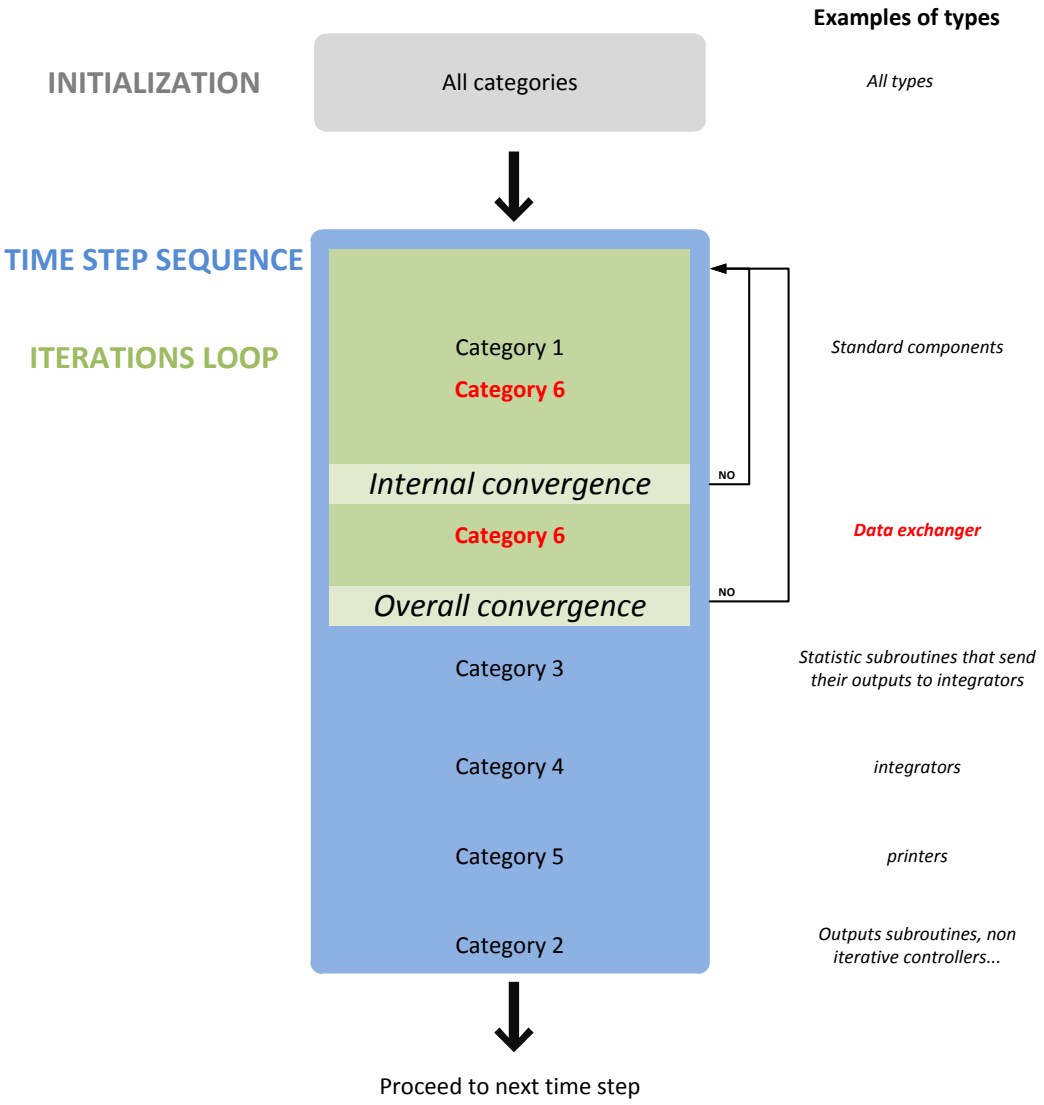


Figure 3-3 Calling sequence with Category 6: Data exchanger Types

In summary, Data exchanger Types (currently only Type 130) have the three main following functionalities:

- Communicate and exchange data in both ways with an external program. This includes simulation variables, as state of a fluid flow for example, but also information about the progression of the simulation (time step, convergence state, etc.).

- Exchange data in a TRNSYS network of Types by passing and receiving data through its inputs and outputs.
- Force the TRNSYS iteration process and prevent the program to proceed to a new time step if the external coupled program has not converged.

3.2.3 TRNSYS kernel main subroutines

In order to implement the new features of the additional category of Types, some modifications to the kernel were implemented. Three subroutines are affected by these changes: *TRNSYS*, which is the principal routine of the program, and two subroutines in charge of the calls to the Types, *Exec* and *Loopex*. A description of original codes followed by modifications brought to them to add the new category of Types is presented below.

- **TRNSYS**

TRNSYS is the main routine of the simulation program. It is launched by the executable TRNExe.exe (or, in a co-simulation, by the Harmonizer) and it is in charge of simulation control. It initializes the simulation, calls other subroutines to read in the input (deck) file, to call components, to perform convergence checking, issuing warning and error messages, and concluding the simulation. TRNSYS is a complex routine interacting with most of the other subroutines and most of the TRNSYS internal data structures. Only information relevant to the implementation of the ESP-r coupling will be presented here.

The variable "intg"

TRNSYS monitors the progression of the simulation and informs the other subroutines about what stage the simulation is at when it calls them. The variable that stores the information on which categories of Types are to be called is the integer "intg". *TRNSYS* increments its value and sends it to the subroutines in charge of calling the Types, *Exec* and *Loopex*. A value of "intg" is not necessarily linked to only one category of Types but each value indicates simultaneously at what point of the simulation the solver is and what are the components to be called at this moment. For

example intg = 2 corresponds to the initialization and all the Types of the simulation have to be called. The different values of "intg" and the corresponding categories of Types are presented later in the description of *Exec*.

Iteration process

The iterations and control of convergence process is also controlled by the *TRNSYS* routine. After each iteration, a series of checks are performed (Figure 3-4) to decide if more iterations are needed, if the program can proceed to the next time step or if, in case of an error, it should abort.

There are four levels of checking:

1. Convergence

   The first thing being checked is the convergence of the components. Input values from Types are compared to those from the previous iteration to determine if a component has converged or not. If convergence is not reached for some components, a new iteration is performed. This is repeated until all the Types of the simulation have converged.

2. Number of calls to a component in a time step

   The total number of calls to the components is limited. It allows continuing the simulation even if convergence has not been reached for all the components at a particular time step. This check is done at the same time as the one for convergence. So if convergence has not been reached but the total amount of calls allowed is exceeded, the program proceeds to the next time step.

3. Number of warnings

   At each time TRNSYS is forced to proceed to the next time step after exceeding the number of calls, a warning message is printed. The number of these warnings is limited as well by a value set by the user. This prevents TRNSYS from not converging for too many time steps. When the limit number of warnings is reached, the simulation is aborted and an error message is written. The simulation can also be aborted if any of the components or kernel routines has triggered a "fatal error" or "stop" message.

4. Stability of the solution

If all the components have converged and there is no warning, *TRNSYS* checks if there are no other error and if the solution is stable. Depending on the results of these tests, the program goes back to the beginning of the time step and restores the initial variables if the solution is unstable. It stops the simulation if errors are found; else it proceeds to post-convergence manipulations and to the next time-step.

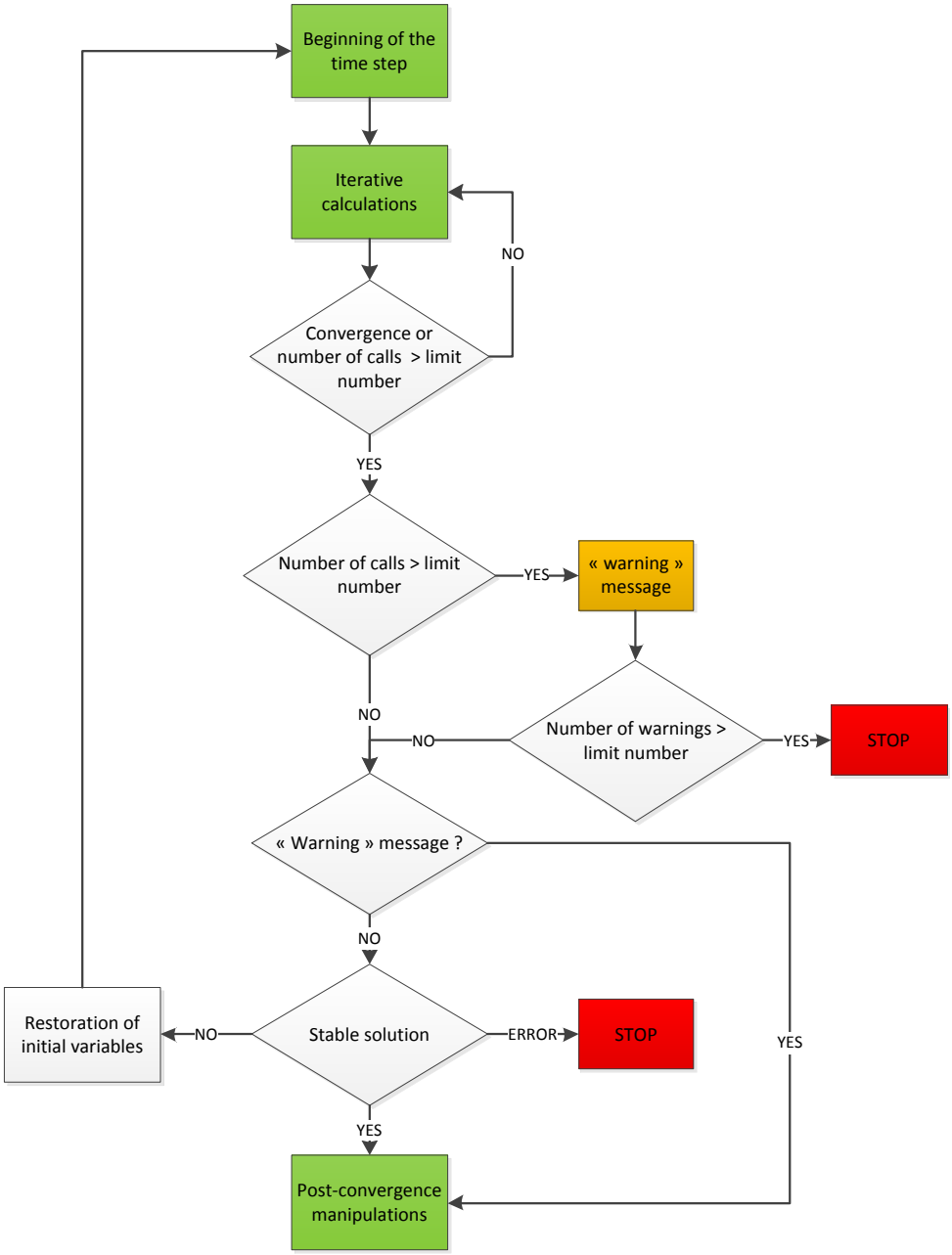


Figure 3-4 Original post iterations process

- **Exec**

Role

Exec ensures the link between the main routine *TRNSYS* and the routine used to call the Types *Loopex*. It orders calls to the components depending on the simulation progress.

Arguments

Table 3-1 Arguments of *Exec* subroutine

Time	Simulation time
T-Local[1]	Array containing the dependent variables for which derivative are evaluated.
DTDT_Local[1]	Local table containing the derivatives of T
intg	Determines which Units are called by *Exec*

Routine that calls *Exec*

- *TRNSYS*

Routines called by *Exec*

- *Loopex*
- *Eval*

Description

The code of this subroutine follows essentially the real call sequence to the different components in a simulation. Depending on the value of the variable "intg" provided by *TRNSYS*, it calls the appropriate Types. It can be split into 8 successive parts:

1. Version signing call

This call allows the identification of the Types at the very beginning of the simulation. The solver then knows the version for which the Types were coded. This ensures backwards compatibility

[1] T_local is a table of variables used by Types that need to be derivated. The calculated derivatives are stored in the table DTDT_local.

with components developed for older TRNSYS versions. The possible versions are 15, 16 and 17.

Value of intg	Types called
-2	All

2. Initialization call

This call helps to perform all the necessary initialization manipulations for some Types. For example defining the size of arrays or performing initial verifications.

Value of intg	Types called
-1	All

3. First call of the simulation

This is the initial time of the simulation. There are no iterations performed at this time. Initial values of all components are collected.

Value of intg	Types called
0	All

4. Iterative call

All the “standard” Types (Category 1) are called at each iteration of a time step, when their inputs change. The very first call of a time step is apart from the other and the value of *Intg* corresponding is 1.

Value of intg	Types called
1,2,3	Standard Types (Category 1)

5. First end-of-time step call (for integrators and output components)

Post-convergence components are called here. Strictly speaking this call occurs at the end of a time step, whether convergence has been reached or too many iterations have been done and TRNSYS has proceeded to the next time step.

Value of intg	Types called
4	Integrators (Category 4)
5	Printers (Category 5)
6	post convergence after integrators and printers (Category 2)
7	post convergence before integrators and printers (Category 3)

6. Second end-of-timestep call

All normal components are called again once convergence has been reached to perform after convergence manipulations like setting storage arrays. Again, strictly speaking this is an end-of-timestep call rather than a post-convergence call.

Value of intg	Types called
9	All

7. Last call of the simulation

The simulation has ended or was aborted. This is a last call to perform final manipulations if necessary.

Value of intg	Types called
8	All

8. Convergence verifications

There is no call to components at this time. Exec performs convergence verifications and updates variables.

Value of intg	Types called
10	None

The "Call" arrays

Exec does not call directly the Types but calls an intermediate subroutine *Loopex*. In order to tell *Loopex* which components have to be called, Exec transmits the array "Call", which includes a logical variable for each Unit indicating if it has to be called or not. For example Call(3) = true means that Unit number 3 has to be called.

The Call array is updated by *Exec* in the simulation depending on the value of "intg" to call the right Types at the right time. During initialization, *Exec* creates 5 models of calling arrays corresponding to what the Call array should be at specific points in the simulation. The different calling arrays are presented below:

Table 3-2 "Call" arrays (part 1)

Call1	Array identifying Units which should be called at least once per time step **True**: Unit is either time-dependent or has derivative (Category 1) **False**: Unit does not need to be called each time step
Call2	Array identifying Units which should be called only at the end of a time step **True**: call Unit only at the end of a time step (Category 2) **False:** Unit does not need the special "only at the end of time step treatment"

Table 3-3 “Call” arrays (part 2)

Call3	Array identifying Units which should be called only at the end of a time step **True**: call Unit only at the end of a time step (Category 3) **False:** Unit does not need the special "only at the end of time step treatment"
Call4	Array identifying Units which should be called only at the end of a time step **True**: call Unit only at the end of a time step (Category 4) **False:** Unit does not need the special "only at the end of time step treatment"
Call5	Array identifying Units which should be called only at the end of a time step **True**: call Unit only at the end of a time step (Category 5) **False:** Unit does not need the special "only at the end of time step treatment"

For each specific moment of the simulation, depending on the value of “intg”, Exec modifies the Call array by equaling it to one of the models established during initialization.

- **Loopex**

Role

Loopex is the routine that calls the Types and provides them all the information about the time and the state of the simulation at the moment of the call.

Arguments

Table 3-4 Arguments of *Loopex* subroutine (part 1)

unit	Number of the Unit that should be executed
j	jcall loops counter
Time	Simulation time
T-Local	Array containing the dependent variables for which derivative are evaluated.

Table 3-5 Arguments of *Loopex* subroutine (part 2)

DTDT_Local	Local table containing the derivatives of T
lastu	Last Unit called
intg	Determines which Units are called by *Exec*

Routine that calls *Loopex*

- *Exec*

Routines called by *Loopex*

- *Type00*
- *SetVal*
- *Trace*

Description

The aim of this routine is essentially to call the Types and it also performs some checks, especially regarding the convergence of the components. It also updates some variables about the simulation current state: if it is the first time step of the simulation, if convergence has been reached for the current time step, etc.

3.2.4 Modifications to the code

The addition of the new category of Types has necessitated some modifications to the routines presented above. New functions and variables have been implemented as well. The changes are explained here and the modifications to the code can be found in Annex 2.

- **New variables**

Info (9)

The first change brought to the code was the creation of the new category of Types. In order to be consistent with the TRNSYS management of Types calling, a new value for Info(9) was created. In addition to the existing values allowed, from 0 to 5, the value 6 was added. Thus

implementation of components characterized with Info(9) = 6 is now possible. They include all Types that need to be called at the same time as standard iterative components (Category 1) but also right after convergence and before post convergence manipulations.

Call7

An additional array (Call7) which marks Units that have to be called for the new category of Types was created in *Exec*. Each value is linked with a Unit and depends entirely of the value of Info(9) of this Unit.

intg

A new value of "intg" (intg = 11) was created as well and defined in *TRNSYS* routine. It corresponds to the moment when all the components have converged (or the maximum number of iterations has been reached), right before performing the end-of-time step manipulations. It is the time to call data exchanger components (Info(9) = 6) once again to check the convergence of the external program.

Info(13)

This variable is a flag indicating that all the Units have converged at the current time step. It is updated by *Exec.* Its value is 0 during iterative calls and 1 during post-convergence calls. A new value has been created for co-simulations. *Exec* set Info(13) = -2 for the external convergence checking call that happens between iterative calls and end-of-time step calls.

CosimConvergenceCheckingTime

This logical variable is meant to be checked by Types of the new category. It is set to "true" when it is the time for exchanger components to check if the other program has converged.

CosimInvocation

The co-simulation process comes with a double level of iterations: internal iterations until convergence of all the Types and iterations between the two coupled programs. In order to clearly

separate the two types of iterations, iterations of the whole system are called “invocations”. This name was chosen in reference to the middleware that controls the overall convergence and keeps calling the programs if convergence has not been reached. All these data are counted by the Harmonizer and relayed to ESP-r and TRNSYS. “CosimInvocation” counts the number of TRNSYS invocations in a simulation.

CosimInvocationIteration

“CosimInvocationIteration” is the number of iterations for the current invocation. It is different from the variable “Info(7)”, the number of iterative calls to a specific Unit in the current time step, which counts the total number of iterations of a component and continue to increment its value if there are several invocations. On the contrary, “CosimInvocationIteration” is reset after each new invocation.

CosimNewInvocation

This variable is a logical flag indicating if the ongoing iteration is the first one being done for the current invocation.

- **New access functions**

In order to make co-simulation variables accessible to other subroutines and especially to Types, new access functions have been implemented.

- *getIsCosimConvergenceCheckingTime()* is to be called by a Type to know if the ongoing call is aimed to check the convergence of the coupled program. The function sends back the value of “CosimConvergenceCheckingTime”.
- *getCosimInvocation()* gives the number of invocations “CosimInvocation”.
- *getCosimInvocationIteration()* gives the number of invocations for the current invocation “CosimInvocationIteration”.
- *getIsCosimNewInvocation()* is used to know if the ongoing iteration is the first iteration of the current invocation. The result is a logical, “CosimNewInvocation”.

- *SetIterationMode(i)* is not a new function but it has been modified to enable the iteration mode (Info(9))to be set to 6 in the case of components from the new category of types used in a co-simulation.

- **TRNSYS**

As presented in Figure 3-5, the post-iterations process in the *TRNSYS* routine was modified. A new check was added right before proceeding to the end-of-time step calls to the Types. This check includes a call to *Exec* with the argument "intg = 11". It indicates to *Exec* to call coupling components only, with the specific task of checking the convergence of the external program.

After the call, *TRNSYS* checks the value of "CosimConv". If CosimConv = true, the overall convergence is reached and *TRNSYS* calls end-of-time steps components before proceeding to the next time step. If not, it calls once again all the Types for a new cycle of iterations for the same time step.

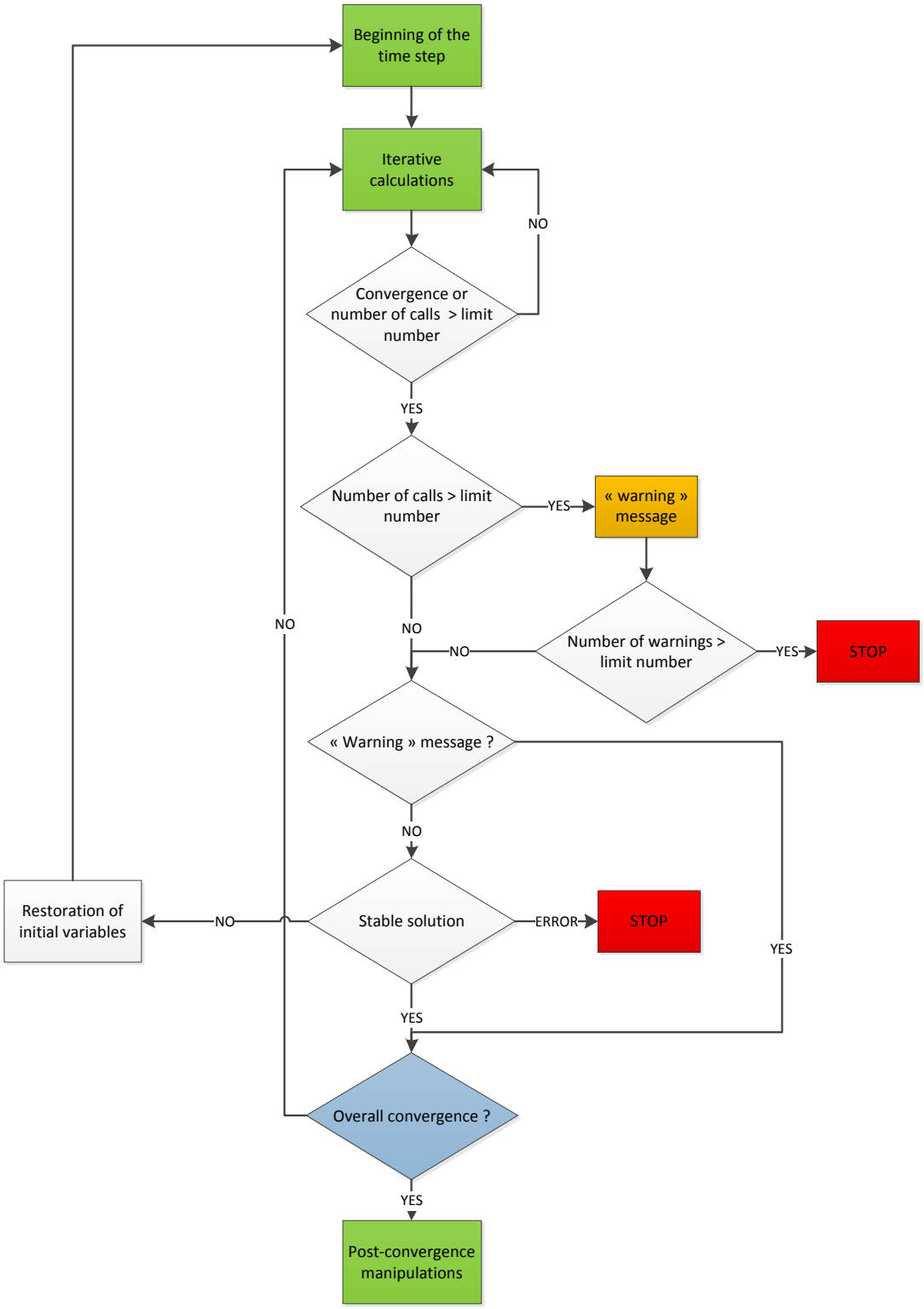


Figure 3-5 Modifications to the post iterations process

- **Exec**

The code of the subroutine *Exec* was also modified to include a new call to data exchanger Types. This call is performed between the standard iterative calls and all the post convergence calls. It is meant to call the components from the new category 6 so that they check the convergence of the external program. This is the new list of *Exec* manipulations:

1. Version signing call
2. Initialization call
3. First call of the simulation
4. Iterative call
5. **Overall convergence checking call**

Value of intg	Types called
11	Data exchanger Types (Category 6)

6. First end-of-time step call
7. Second end-of-time step call
8. Last call of the simulation
9. Convergence verifications

Step 5 with calls to Category 6 Types is executed when “intg” is equal to 11. *Exec* sets the “Call” array equal to the model of array “Call7”. This new array specific for this point of the simulation (overall convergence checking time) has been created beforehand during the initialization period. Changes of other models of calling arrays have also been made. They enable the new category of Types with Info(9) = 6 to be called with the standard iterative Types from Category 1. Values of “Call1” linked to data exchanger Types are set to “true” and values from the other models of calling arrays are set to “false”.

- **Loopex**

Modifications done to this subroutine are limited to the addition and update of the new logical variable “CosimConvergenceCheckingTime”. This variable is set to ”true” by *Loopex* when Info(13) = -2. In all the other cases it remains “false”.

3.3 TYPE 130

The Data exchanger component created for running co-simulation with ESP-r is called Type 130. Its role is to communicate with the Harmonizer and manage the control of internal iterations. In the exchange of data process, Type 130 works as the complement of the coupling components in ESP-r.

3.3.1 Generalities in Types coding

Calls structure

Each component routine is organized in 6 parts corresponding to a specific action to be executed, depending of the kind of call to the Type. The structure is the same for all the categories of Types but not all the components have specific actions to perform at every call. The organization of a component code is similar to the one of the subroutine *Exec* (cf. 3.2.3):

1. Version signing call
2. Initialization call
3. First call of the simulation
4. Standard iteration call
5. End-of-time step call
6. Last call of the simulation

Inputs/Outputs

Communication with other components is realized by a system of inputs and outputs data. Outputs are data calculated by the Type that can be sent to other components. Inputs are the data

coming from other components used by the Type. Their number is defined at the second call to the Type (Initialization) depending on what the user specified in the deck file.

Code and Proforma

A TRNSYS component requires two files. On one hand the source code (in Fortran or another programming language) programs all the actions that the Type performs in a simulation: collect data from the inputs, perform the calculation, set output values, perform additional actions. The code is either compiled within TRNSYS main DLL or in an external DLL. On the other hand the proforma can be thought of as the Type "black-box description". It is used by the Simulation Studio interface to define the number and the nature of inputs, outputs and parameters of the Type when the Type is used and configured in a simulation. When a simulation is run from the Simulation Studio, all the information on component parameters, input-output connections and simulation controls is written to the TRNSYS input file (deck file) and then read by the kernel. the proforma must be consistent with the parameters/inputs/outputs description of the component.

3.3.2 Type 130 communication process

Type 130 belongs to the data exchanger Types category and is to be used in a coupled simulation with the building performance energy modeling software ESP-r. It works as a multiple hydronic and/or air connector. It receives air and fluids states (temperatures, flow rates) from ESP-r, feeds them to other components in a TRNSYS simulation, and then sends other air and fluid states back to the external program. It exchanges data with ESP-r within the time-step. The standard TRNSYS procedure for connecting components is used to map other Types outputs to Type 130 inputs and Type 130 outputs to the inputs of the other TRNSYS Types as shown in Figure 3-6. Outputs of Type 130 represent data coming from ESP-r whereas inputs are data sent to ESP-r.

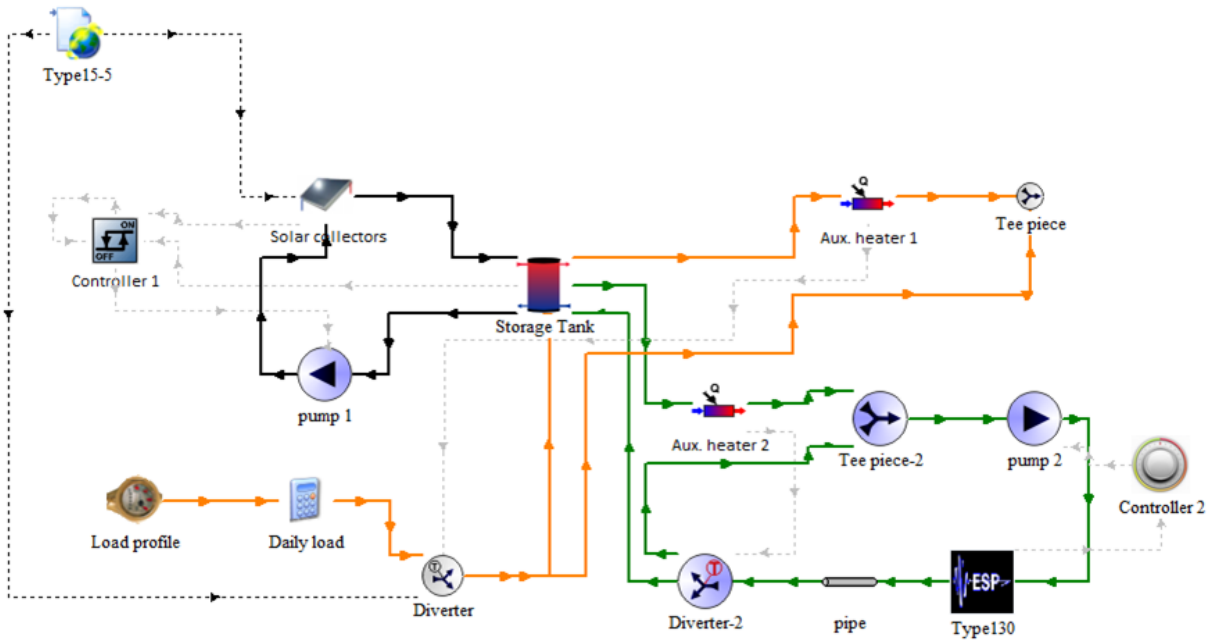


Figure 3-6 Network of Types including Type 130

Type 130 initially loads the Harmonizer DLL and then exchanges data by calling two functions in the Harmonizer: "GetEsprData" and "PassDataToEspr" (cf. Figure 2-15). The required variables are passed via a shared derived data structure (DDS): CosimData described previously in section 2.3.3. Variables are distributed into three categories: Hydronic Coupling Components (HCC), Air Coupling Component (ACC) and Zone Data. This is similar to the structure of the coupling components in ESP-r. The user can configure Type 130 to use any number of coupling components of each Type and any number of zones, up to the maximum allowed.

Type 130 is unique in that it can prevent the TRNSYS engine from proceeding to the next time-step when TRNSYS has converged but there is no overall convergence for the co-simulation (TRNSYS and ESP-r). It is called directly after internal convergence to determine whether the simulation can proceed to the next time-step. At this moment, Type 130 calls the function “GetSystemConv” in the Harmonizer. If overall convergence has been reached, TRNSYS performs the end-of-timestep actions and then proceeds to the next time-step. If not, Type 130 calls “GetEsprData” again and new iterations of the same time-step are performed, after getting new data from ESP-r.

3.3.3 Type 130 inputs, outputs and parameters

The role of Type 130 is to communicate with ESP-r. Its inputs and outputs are used to exchange data between a network of TRNSYS Types and ESP-r. Outputs are data coming from ESP-r and transmitted by Type 130 to other Types. Inputs are variables from other components collected and sent to ESP-r by Type 130. Figure 3-7 shows the inputs/outputs organization of the component, as implemented in the source code and the proforma.

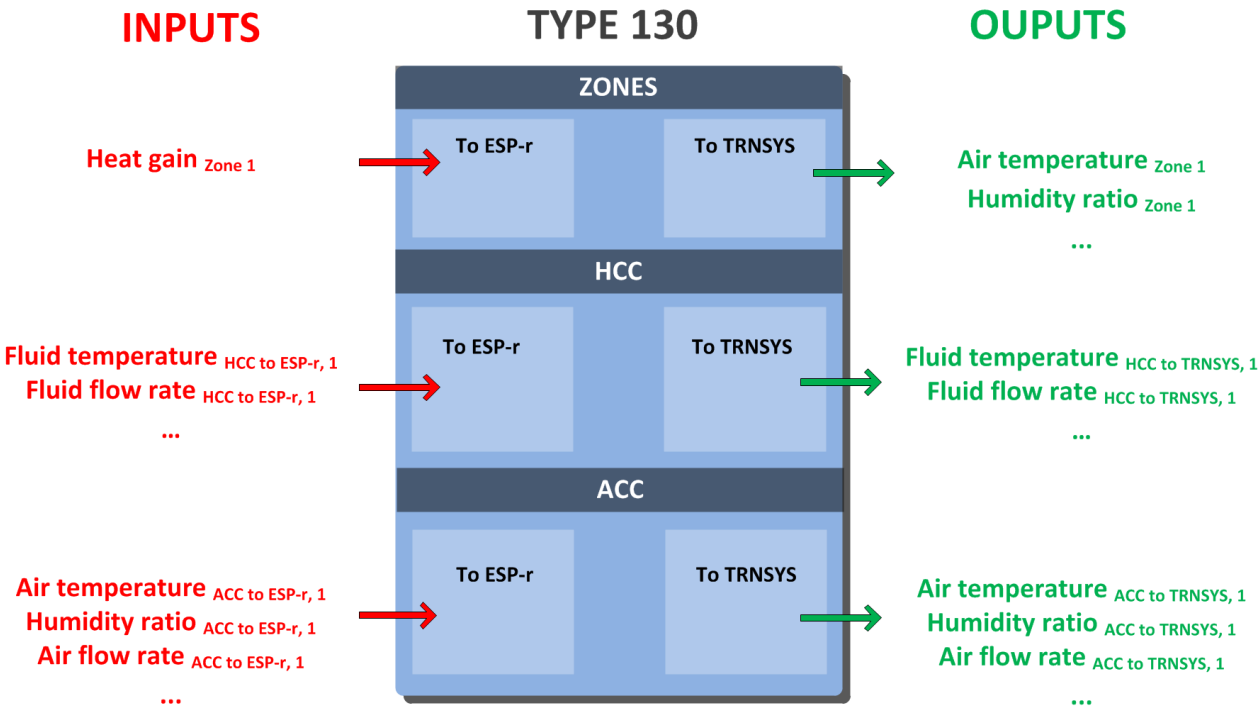


Figure 3-7 Inputs and outputs organization

Inputs and outputs are classified in three groups: building zones, HCCs ports and ACCs ports, and each group contains a subset of data. Information on zones includes heat gains transferred from mechanical equipment modeled in TRNSYS to a specific zone in ESP-r. This is passed through an input of Type 130. On the other hand, air temperature and humidity ratio of building zones can be passed from ESP-r to TRNSYS through outputs of Type 130. ACC and HCC ports represent respectively data from air flow and fluid flow links. In the case of HCCs, fluid temperature and flow rate is exchanged for each link. For ACCs, the temperature, the humidity ratio and the flow rate of the air is transferred in the two ways. Figure 3-8 shows the links between Type 130 and other components: ESP-r coupling components on the left-hand side and the other TRNSYS Types on the right-hand side.

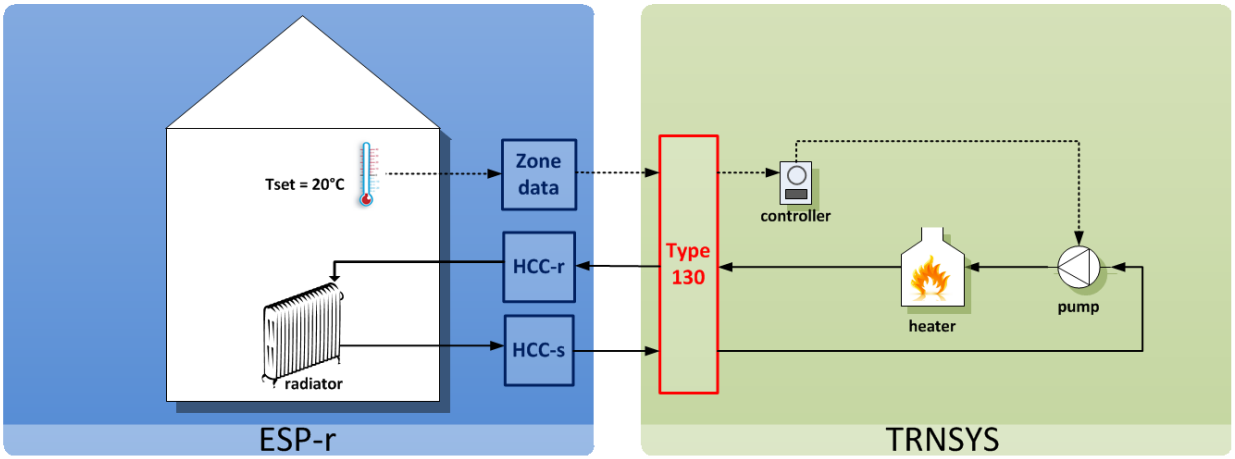


Figure 3-8 Coupling components connections

Parameters define the number of inputs and outputs of Type 130. This allows the user to customize the Type and adapt it to the required number of links to ESP-r. There are 7 different parameters:

1. Mode (standard or test)
2. Number of zones
3. Number of HCC to TRNSYS
4. Number of HCC to ESP-r
5. Number of ACC to TRNSYS
6. Number of ACC to ESP-r
7. Number of forced iterations (only in test mode)

3.3.4 Standard and test modes

The parameter "mode" allows the user to choose between using Type 130 normally and exchange data with ESP-r (mode = 0) or to use the "test" mode of the type (mode = 1).

If the test mode is selected (mode = 1), Type 130 does not load the Harmonizer DLL. Instead, it loads a dedicated DLL (Harmonizer_TestMode.dll), which has no link with the Harmonizer executable program or with ESP-r. "Harmonizer_TestMode" only communicates with Type 130, and sends back constant output values for a maximum of 2 zones, 2 HCCs and 2 ACCs. This

functionality can be used to debug the TRNSYS part of the co-simulation by running the "co-simulation project" entirely within TRNSYS. Setting the parameter mode to the value 1 in the proforma brings up a new parameter: NumIterations. It forces the number of iterations for all the Types connected to Type 130 outputs to be called at least the number of time defined with this parameter. This can be used to simulate the impact of additional iteration caused by a co-simulation.

3.3.5 Type 130 code

The complete Type 130 code is given in Annex 3. This part describes the different actions of Type 130 throughout the calls structure.

1. **Version signing call**
   - Inform the kernel that Type 130 was created under the version 17 of TRNSYS.

2. **Initialization call**
   - Get the number of coupled components from the parameters value and set the correct number of inputs and outputs.
   - Inform the kernel that it is a data exchanger Type
   - Load the Harmonizer DLL
   - Get pointers to the Harmonizer functions: GetEsprData, PassDataToEspr and GetSytemConv.

3. **First call of the simulation**
   - Get values from Type 130 inputs and pass them to ESP-r (call to PassDataToEspr).
   - Get data from ESP-r (call to GetEsprData) and set outputs values.

4. **First call of a new time step**
   - Get data from ESP-r (call to GetEsprData) and set Type 130 outputs.

5. **Standard iteration call**
    - Keep passing information received from ESP-r at the beginning of the time step to other TRNSYS components through Type 130 outputs.
6. **Overall convergence checking call**
    - Pass simulation data for ESP-r to the Harmonizer and tell the Harmonizer that TRNSYS has converged (call to PassDataToEspr).
    - Check if ESP-r and overall convergence has been reached (call to GetCosimConv).
    - Tell TRNSYS if overall convergence has been reached: define CosimConv = true if there is convergence or false in the other case.
    - Get new data from ESP-r if there is no overall convergence (call to GetEsprData) and set Type 130 outputs.
7. **Post convergence call**
    - Type 130 does nothing at this call.
8. **Last call of the simulation**
    - Last call to PassDataToEspr to tell the Harmonizer that simulation is completed in TRNSYS.

Type 130 updates co-simulation state information for ESP-r and TRNSYS at each time it is called.

In summary, a list of Type 130 operations compared to a standard TRNSYS Type is presented in Figure 3-9 Summary of Type 130 calls and operations

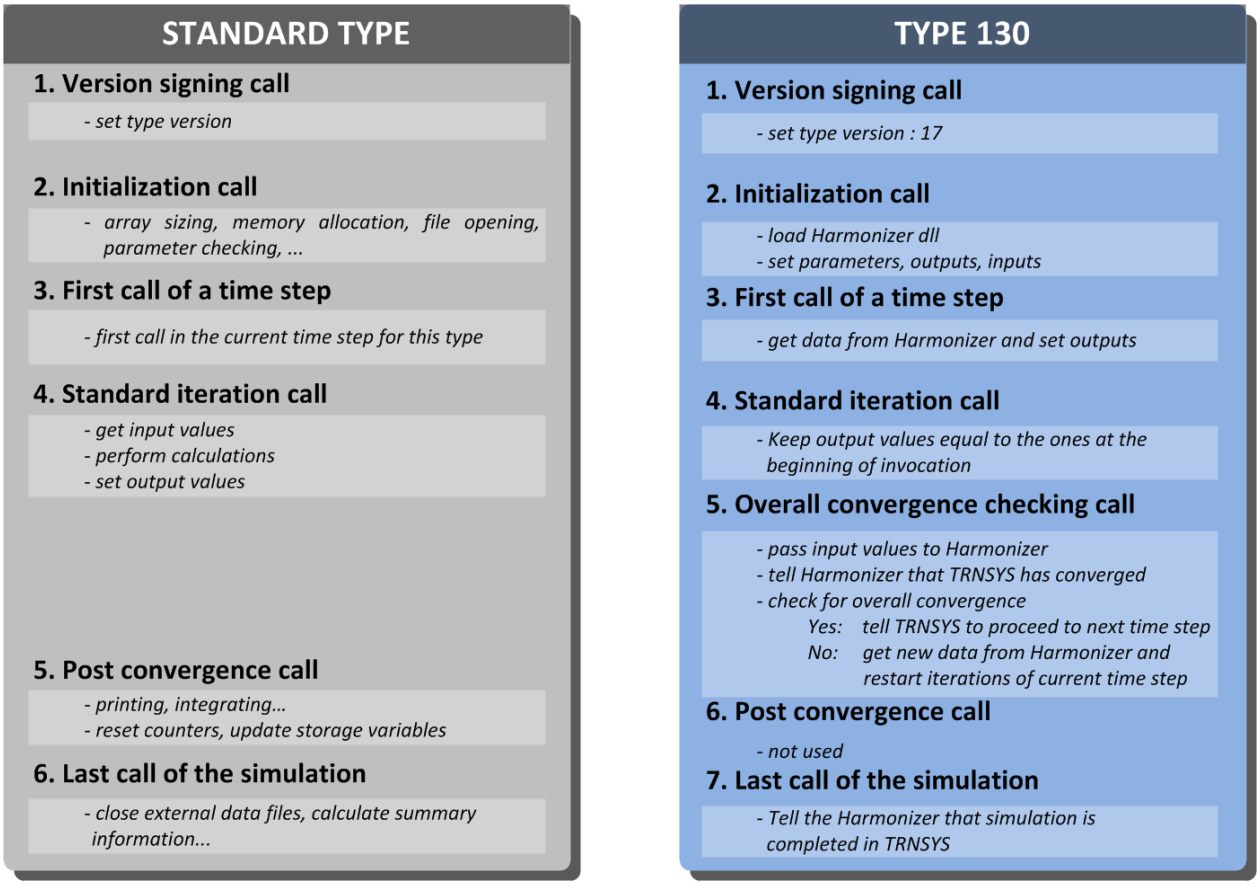


Figure 3-9 Summary of Type 130 calls and operations

CHAPTER 4 DEMONSTRATION AND TESTS

This chapter presents the tests and the results obtained with the co-simulator. From basic data exchange to complete co-simulation, the testing and debugging phase was a significant part of the project work. TRNSYS-only tests and the TRNSYS-side of co-simulation tests and debugging were performed by the author of this MASc thesis with input from the Design Team. Both programs simulation files for these tests are available on the central repository for ESP-r's source code (Macdonald & Jost, 2012). Results of demonstration tests are also published in two conference papers (Beausoleil-morrison et al., 2012; Macdonald, Jost, Beausoleil-morrison, Mcdowell, & Ferguson, 2012).

4.1 Preliminary tests

A few programmatic checks were performed at the very beginning of the implementation phase in order to verify the inter DLLs communication design. Compilation and testing of three simplified DLLS representing ESP-r, TRNSYS and the Harmonizer was realized with success. The very basic Harmonizer was able to create threads initiating both coupled programs and exchange data with them. The next tests were executed throughout the project to check if communication between the three programs worked as expected. The following sections will describe the preliminary testing procedure for modifications on the TRNSYS side.

4.1.1 External data transfer and iteration control

The main modification to TRNSYS was the addition of a new category of Types and its capabilities to exchange data with an external DLL and control TRNSYS iterations loops. Prior to trying to pass and receive data with the real Harmonizer, a test Harmonizer DLL was created. This DLL was loaded by Type 130 and included the same functions as those that Type 130 is supposed to call in the real Harmonizer. The functions send data, as simulation variables or flags, to TRNSYS. Variations of these data helped to test and debug Type 130 and the modified kernel subroutines. It also proved that the design of the coupling worked: data from another DLL were conveyed to other TRNSYS components and the new Type was able to prevent TRNSYS from

proceeding to the next time-step when the middleware indicated not to do so. This test Harmonizer DLL, renamed Harmonizer_TestMode, still exists. It has been improved and can be used by a co-simulator user to test the TRNSYS part of the coupled simulation before using ESP-r (see the Test mode of Type 130 described above).

4.1.2 Data exchange with ESP-r (Test A)

After the concluding tests with the test middleware, real exchange of data with ESP-r and the Harmonizer was performed. Both double precision and logical variables were passed back and forth between the two programs. This step helped to verify that data was passed without being corrupted.

Data exchange

A first co-simulation test case called Test A was implemented. It does not represent any real system but each program receives data, modifies it and passes it to the other program. In ESP-r, a very basic plant system is modeled and sends to TRNSYS a temperature of a fluid associated with a flow rate. On the TRNSYS side, the project file includes only Type 130, an equation block and a printer. The equation block receives the temperature and the flow rate coming from ESP-r and relayed by Type 130. It adds respectively 1 and 2 to the temperature and flow rate values, and sends the modified variables to Type 130 and ESP-r. Values of exchanged variables were monitored at different points in the coupling to check that there was no corruption of data at any step.

Convergence handling

Convergence control by the Harmonizer was also tested. To simulate long cycles of iterations and control the number of loops, a Type preventing TRNSYS from converging was created. The idea was to force TRNSYS iterating in a “normal” way, i.e. when inputs of standard Types keep changing in a simulation. This new Type, known as Type 131, outputs oscillating values for a fixed number of iterations. If that output is connected to another Type in a TRNSYS network, the kernel continues calling this Type until its input remains constant. The creation of this Type allowed defining precisely the number of internal iterations in TRNSYS and helped write the Harmonizer`s code.

4.2 Water based heating system (test B)

This section contains the description of coupled simulation test cases that validates the co-simulator's ability to simulate a hydronic system.

4.2.1 System tested

The system implemented here modeled a water based heating system for a single-zone building. As shown in Figure 4-1, the building and a radiator are modeled in ESP-r. The rest of the system is implemented in TRNSYS. Water supplying the radiator is heated up to 75 °C and circulates at a flow rate of 500 kg/hr.

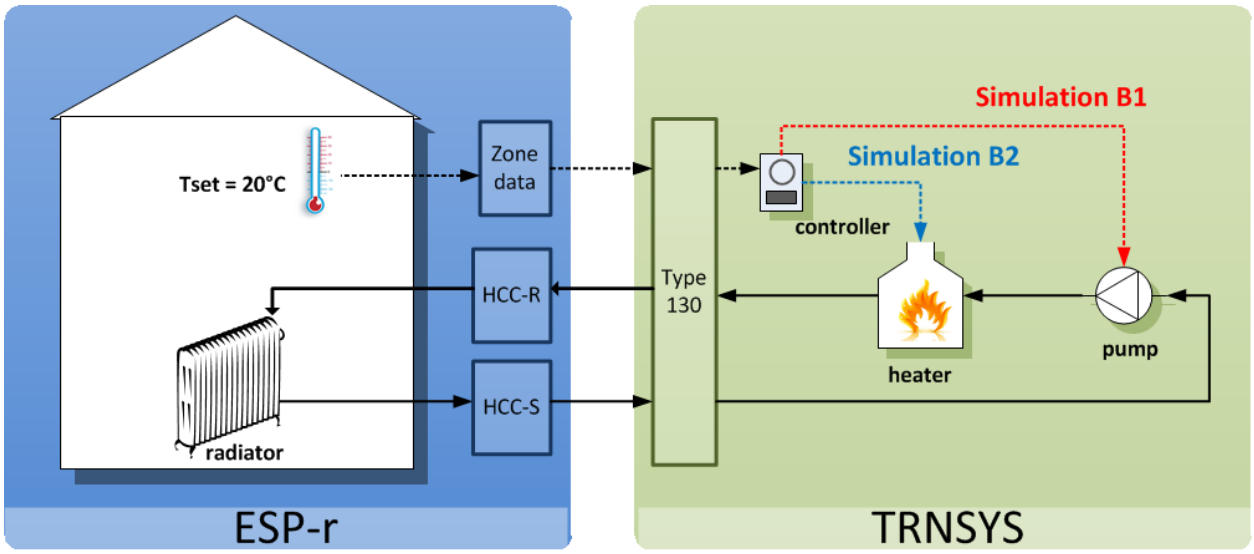


Figure 4-1 Schematic of test B system

The HVAC system in TRNSYS comprises: a boiler and pump activated by a controller trying to maintain a constant room temperature. There are two co-simulation variants:

B1 where an on/off controller is used to control the flow rate of a constant temperature stream of water

B2 where an on/off controller is used to control the temperature of a constant flow rate of water

In both test cases the dead band of the controller is 2°C. Since the heating set-point is 20°C, the system is activated by the controller when temperature of the air in the zone decreases below 19°C and is turned off when the air temperature is higher than 21°C.

4.2.2 ESP-r

The building modeled in ESP-r is based upon BESTEST case 600 (Judkoff & Neymark, 1995). It uses a plant network consisting of a sending and receiving HCC (Hydronic Coupling Component) and a radiator in ESP-r.

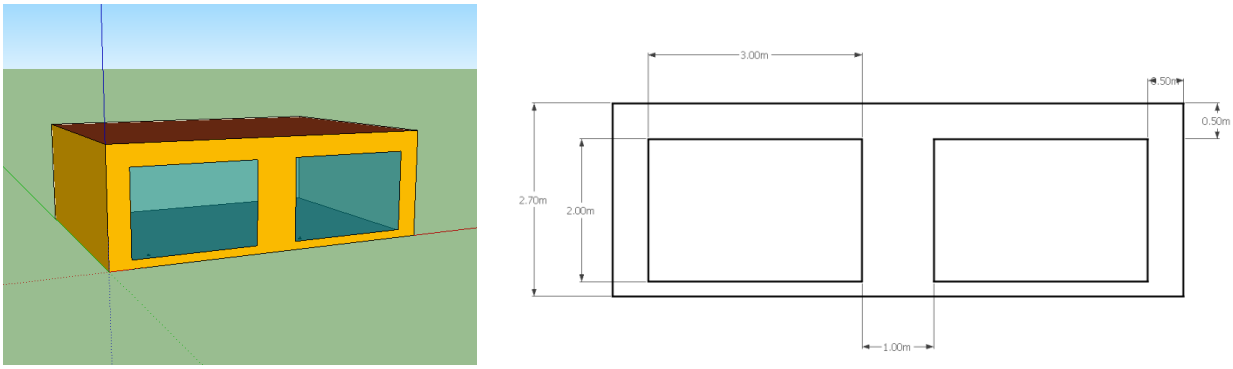


Figure 4-2 Overview and front view of BESTEST case 600 building

4.2.3 Simulation using TRNSYS only

In order to compare results obtained from the co-simulation, a test case implemented only in TRNSYS was created. The TRNSYS part already existing in the coupled simulation is the same here. As presented in Figure 4-3, the “red” loop with the pump, the heater and the controller is unchanged in comparison to the co-simulation project. Type 130 has been replaced by components that were implemented previously in ESP-r: the building and the radiator. A weather data reader Type loading the same weather file as ESP-r in the co-simulation case is also added here.

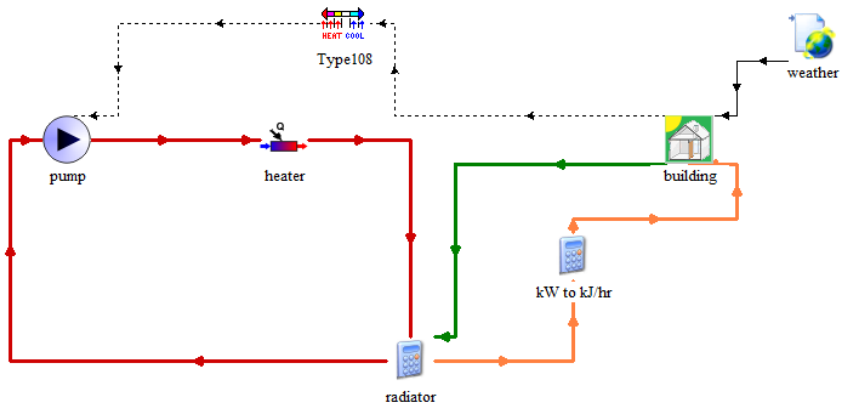


Figure 4-3 TRNSYS only simulation for Test B

The radiator model implemented for this simulation is based on the following equation (ASHRAE, 2008):

$$q = c(t_s - t_a)^n$$

Where:

Table 4-1 Radiator model parameters

Heating capacity	q	W
Constant determined by test	$c = 50$	
Arithmetic average of the entering and leaving water temperature	t_s	°C
Room air temperature	t_a	°C
Exponent for cast-iron radiators	$n = 1.2$	

The room air temperature is known at every time step. To define the temperature of water exiting the radiator and energy injected into the zone, an energy balance on the radiator is performed:

$$q = \dot{m}_w C_p(t_{out} - t_{in})$$

Where:

Table 4-2 Description of radiator governing equation variables

Water mass flow rate	$\dot{m}_w = 500$	kg/hr
Water specific heat	$C_p = 4.19$	kJ/kg.K
Entering water temperature	t_{in}	°C
Leaving water temperature	t_{out}	°C

The building is modeled by the multi-zone building component Type56, which was configured to model BESTEST Case 600.

4.2.4 Results analysis

Results obtained from co-simulation prove that control of the system by TRNSYS based on data transmitted by ESP-r is effective. The temperature of the thermal zone is maintained at a value of 20 °C. Moreover, a comparison of results from a co-simulation with a TRNSYS only simulation (Figure 4-4) shows that the evolution of zone air temperature is similar.

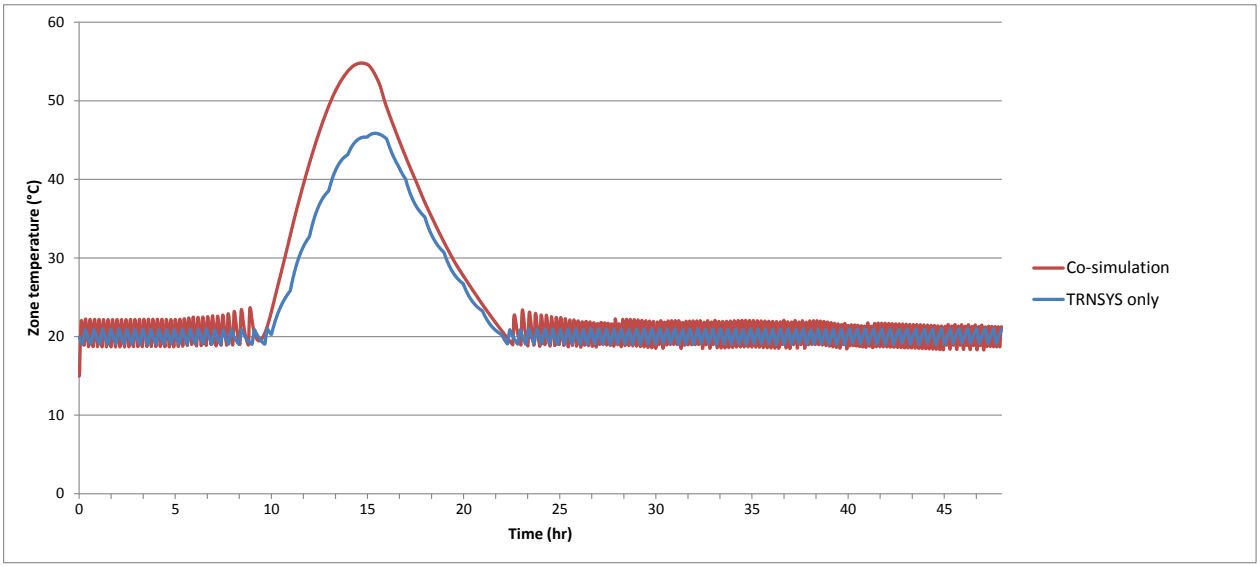


Figure 4-4 Comparison of zone air temperature for two winter days

The graph represents the temperature of the air in the building for a sunny and a cloudy winter days. Since the building has a largely glazed façade oriented towards the South and there is no cooling system, high temperatures are reached in the afternoon of day 1. The rest of the time there is no solar contribution to maintain the temperature of the zone higher than 20 °C, therefore the heating system is ON. Temperatures coming from the two simulations are close, yet we can notice some differences. The afternoon peak is higher in the case of the co-simulation. The same effect can be observed with variations of temperature around the set-point, which are greater with results obtained with the co-simulation case. These variations are explained by the fact that the radiator and building models are not the same in the two programs, even if an effort was made to reconcile their parameters. The main difference is that the model of radiator is transient in ESP-r whereas a steady state model with no mass has been implemented in TRNSYS.

The two following graphs presented in Figure 4-5 show more in details that the whole system is working properly for a coupled simulation. On the right side, temperature of the zone (blue) and water flow rate (green) are plotted for the B1 simulation. The temperature of the water provided to the radiator is constant, but the flow rate is variable. The graph shows that the pump is turned OFF as expected when the temperature of the air is higher than 21°C and switched ON when the temperature is under 19°C. The mechanical system controlled in TRNSYS is able to react to and control a temperature of a thermal zone implemented in ESP-r. It can be noted that the temperature of the air continues to rise after the flow of the water to the radiator is stopped. This is explained by the capacity of the water in the radiator. Even if there is no more hot water supplied to the radiator, the water inside the radiator is still warm enough to heat the air for a certain time.

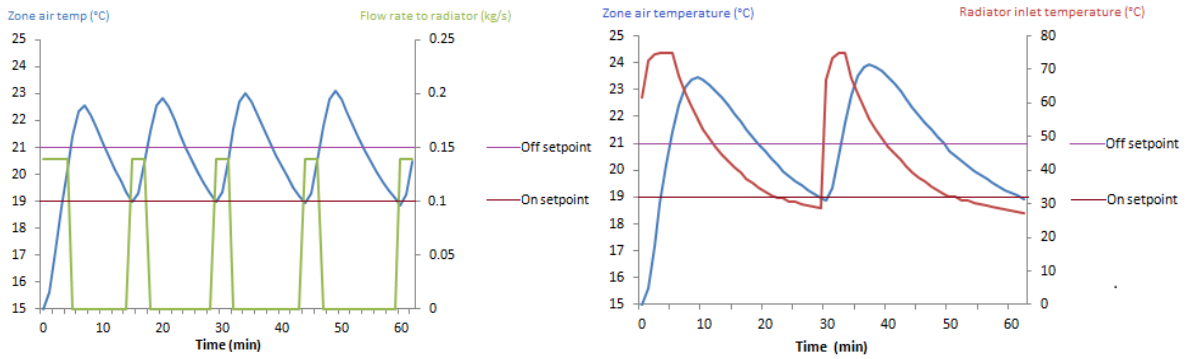


Figure 4-5 Evolution of the zone air temperature for the two test cases B1 (right) and B2 (left)

The second graph of Figure 4-5 shows results from the B2 simulation, where the flow rate is kept constant but the temperature of the water provided to the radiator changes. The air temperature, (blue) and the water temperature at the inlet of the radiator (red) are represented. As long as the temperature of the zone remains lower than 21 °C, the boiler heats the water up to a maximal temperature of 75 °C. Then the temperature of the air decreases slowly, and when it goes under 19 °C, the water is heated again.

Results from the previous simulations are not optimized. The control of the temperature works but the amplitude between the highest temperatures (around 23 °C) and the lowest ones (around 19 °C) is large. The lack of accuracy in tracking the setpoint comes from the ON/OFF nature of the simulated control system. Another simulation was created with a PID controller for the water flow rate. Figure 4-6 shows that the temperature curve is smoother in this case and the temperature of the zone is close to 20 °C.

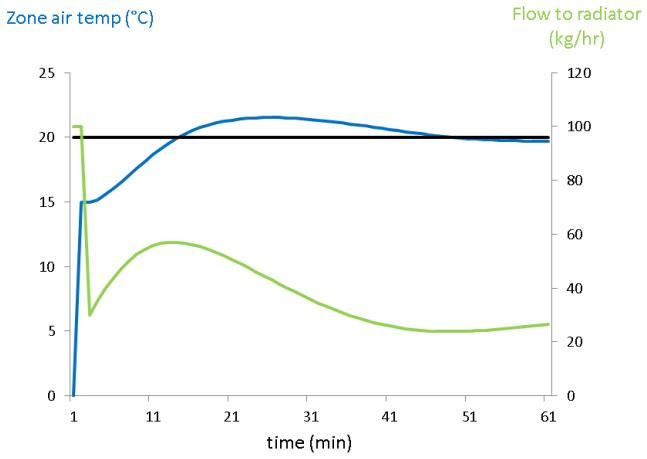


Figure 4-6 Evolution of the zone air temperature and water flow rate with a PID controller

4.3 Air based heating system and humidity transfer (test D)

The tests presented here were created in order to check the correct transfer of humidity in a co-simulation. Two cases of studies were developed. The first modeled is a single zone building with constant boundary conditions without any source of humidity. Another model was tested then with the same building but this time with a constant internal source of humidity. In both cases a ventilation system adds fresh air at a constant humidity rate and constant flow rate.

4.3.1 No humidity source

- **System**

Figure 4-7 illustrates the system implemented for this test. A simple isolated thermal zone modeled in ESP-r is humidified by a ventilation system in TRNSYS.

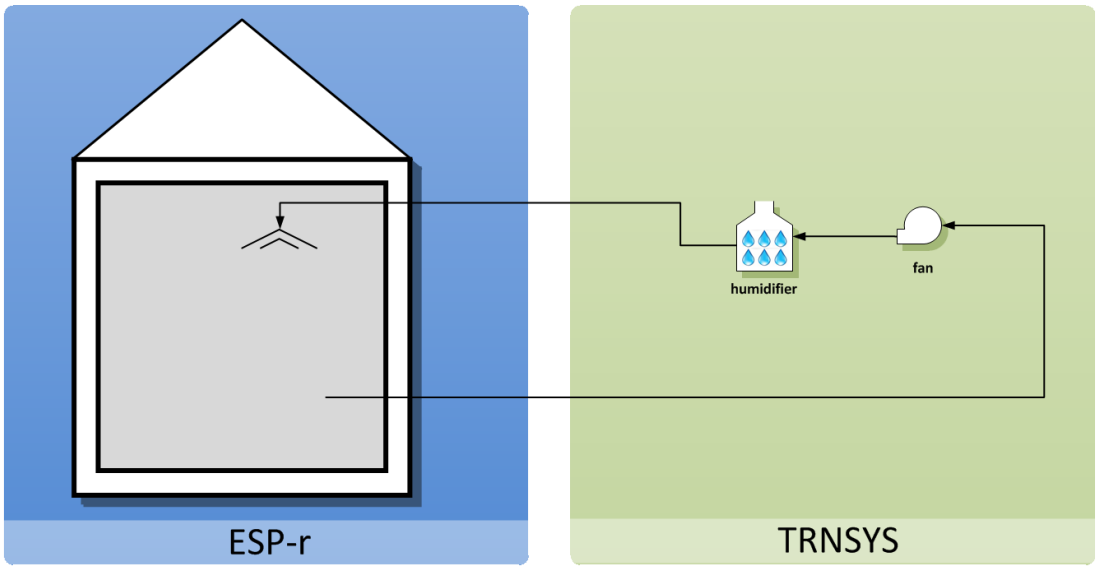


Figure 4-7 Schematic of test D system without humidity source

- **Settings:**

Table 4-3 Settings of Test D without humidity source

Air flow rate	$\dot{m}_a = 1000\ kg/hr$
Water flow rate	$\dot{m}_w = 3\ kg/hr$
Humidity ratio of supplied air	$w_{in} = \frac{\dot{m}_w}{\dot{m}_a} = 0.003$ kg/kg

The building has constant boundary conditions. The climate file used in ESP-r has zero solar radiation, an ambient temperature of 20 °C and a relative humidity of 50 %.

- **Results**

The test shows the correct results for transient conditions as well as for steady state. In Figure 4-8, we can observe the evolution of the humidity ratio of the air in the zone. The supplied air contains a constant quantity of humidity. As predicted, the value of humidity ratio of the zone converges to the one of humidity ratio of the supplied air.

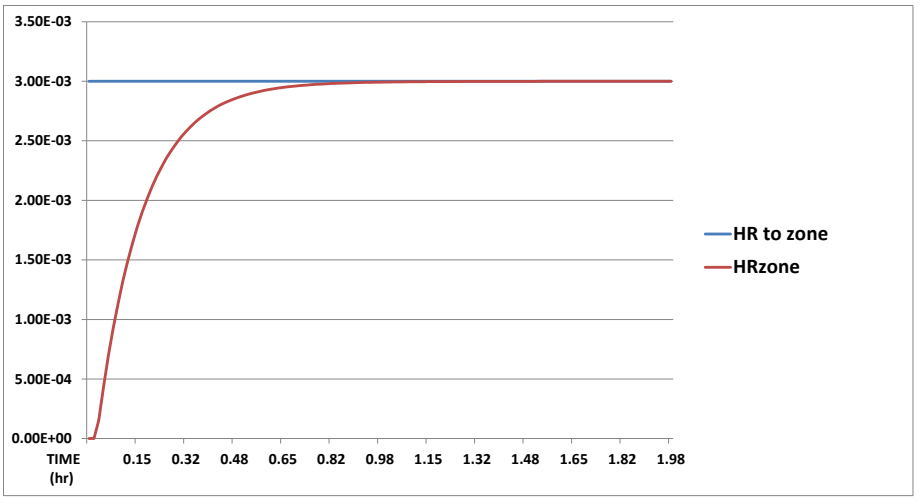


Figure 4-8 - Transient state humidity ratios

The test is then continued to a week. Differences between the humidity ratio of the air injected in the zone and the air leaving the zone are compared and represented in Figure 4-9. The graph shows that the two humidity ratios are similar. The maximum difference between the two values is less than 10^{-7} and can be attributed to rounding errors inherent to computers.

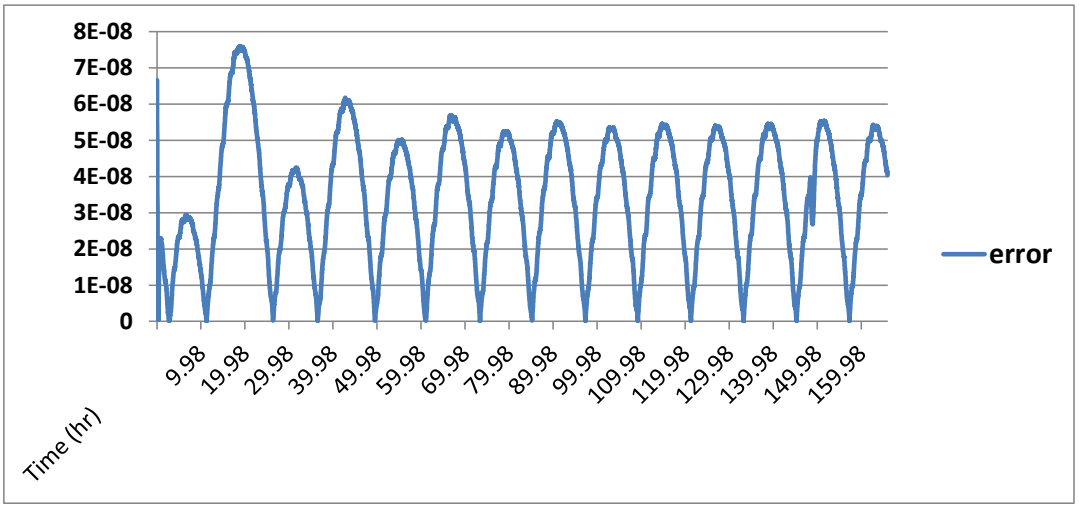


Figure 4-9 - Differences between HR send to the zone and HR of the zone

4.3.2 Constant humidity source

- **System**

The building is the same as in the first test case. The humidifying system is simplified to a system that sends air at a constant absolute humidity level without changing the temperature of the air (i.e. the supply air temperature is the temperature of the thermal zone). A source of humidity has been added inside the thermal zone (latent heat gain) for this second simulation.

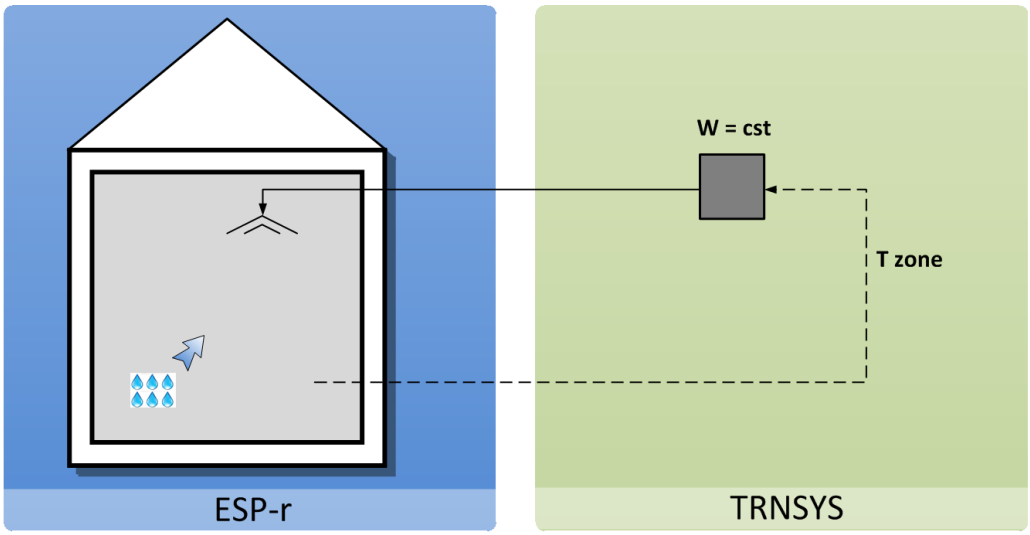


Figure 4-10 Schematic of test D system with constant humidity source

- **Settings:**

Table 4-4 Settings of Test D with Humidity source

Air flow rate	$\dot{m}_a = 1000\ kg/hr$
Humidity ratio of supplied air	$w_{in} = 0.003$ kg/kg
Latent energy source	$\dot{Q}_L = 60$ W

The building and the climate file are the same as those used in the first case.

Results

For this test a simulation of one week (168 hours) was performed. Results obtained at the end of the simulation are presented below:

Temperature of the air in the zone (DB): T_{168} = 16.3 °C

Humidity ratio of the air in the zone:	**$HR_{zone\ 168}$ = 0.00308537 kg/kg**

Verification of the value of the amount of humidity in the zone with a mass balance:

$$\dot{m}_a \,.\, w_{in} + \dot{m}_w \;=\; \dot{m}_a \,.\, w_{out}$$

Where: $\dot{m}_w$ is the mass of water added in the zone in kg of water/hr

w_{out} is the humidity ratio of the air leaving the zone

The heat gain in ESP-r is purely latent. We can assume that it corresponds to adding a given flowrate of saturated steam at the room temperature, and we have:

$$\dot{Q}_L = \dot{m}_w . h_w$$

Where: h_w is the enthalpy of the water added in the zone in kJ/kg of water

The enthalpy of the added water is:

$$h_w = 2501 + 1.86\, T_{168} = 2531\ kJ/kg$$

and:

$$\dot{m}_w = \frac{60\ \text{W} \cdot 3.6\ \text{kJ/h-W}}{2531\ \text{kJ/kg}} = 0.08534\ \text{kg/h}$$

By solving the mass balance, we find:

$$\boldsymbol{w_{out} = 0.00308534\ \text{kg/kg}}$$

We find the same value as the one from the co-simulation so humidity transfer between the two programs can be validated.

The error/difference between the value calculated and the one obtained numerically is:

δ = 2.95 E-08. kg/kg

(or a relative error of less than 0.001 %)

4.4 House serviced by a DHW/space heating solar combi-system (test C)

The co-simulation tested here includes a simple house (modeled in ESP-r) and a solar combi-system (modeled in TRNSYS) used for space heating and domestic hot water production. The models and obtained results are described below.

The TRNSYS part of the combisystem model was developed and configured by the author of this MASc thesis with input from the Design Team. The building model in ESP-r was developed and implemented by the Carleton University team. Debugging, model tuning and results interpretation were a team effort. This test was a project deliverable requested and the following section is part of a report submitted to Natural Resources Canada. The lead author for the deliverable was the author of this MASc Thesis, who also created the TRNSYS part of the co-simulation model.

4.4.1 System tested

The simulated system includes a 3-zone house and a solar combi-system used to meet the space heating load of the house and to provide domestic hot water. A schematic of the whole system is shown in Figure 4-11, with the mechanical system modeled in TRNSYS and the building in ESP-r.

The house is modeled as a 3-zone building where the temperature of the main floor is kept at 20 °C by the solar combi-system. This exercise focuses on solar heating, so cooling and natural ventilation are not modeled. This results in very high zone temperatures on sunny days, particularly during the summer.

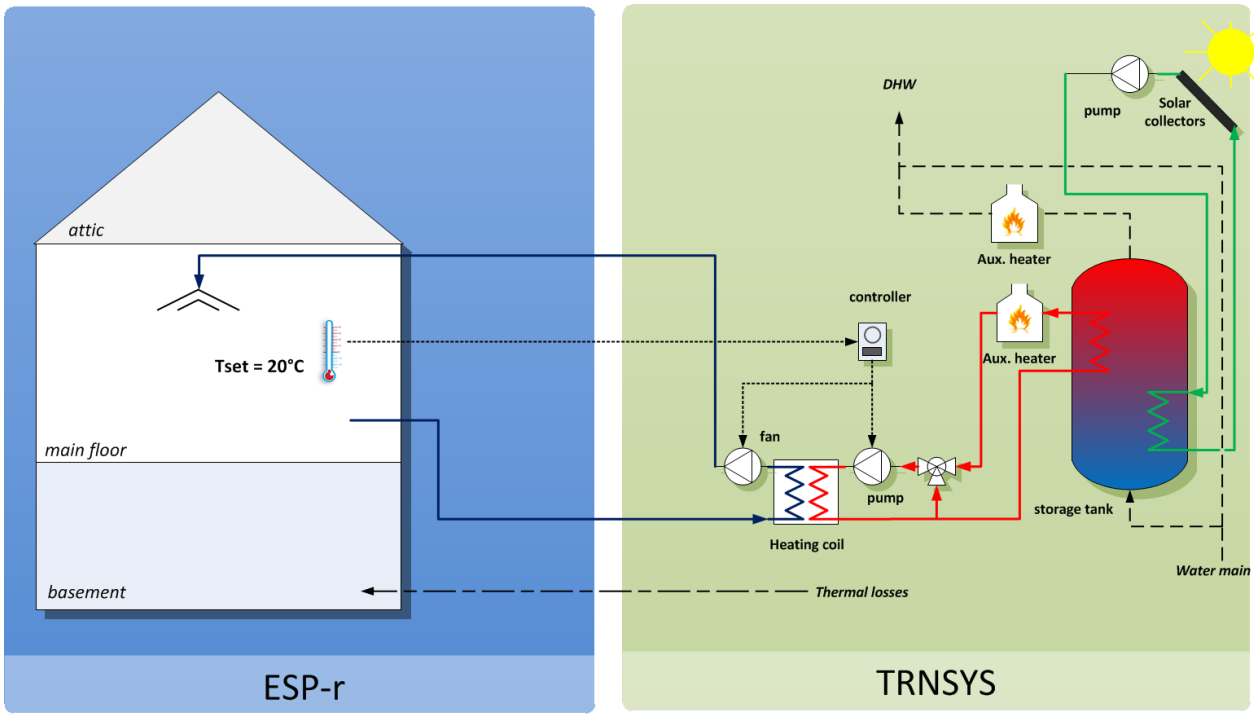


Figure 4-11 Schematic of test C system

The system configuration and parameters have been selected to obtain a relatively simple model in TRNSYS. They have not been optimized for energy performance and the model should be seen as an example of a co-simulation, not as an example of an efficient solar combi-system. The system consists of a domestic hot water storage tank with two heat exchangers. The first heat exchanger (green), located in the lower part the tank, transfers heat from the water-glycol loop connected to solar thermal collectors. The second heat exchanger (red), located in the upper part of the tank, provides heat to an air-handling unit supplying warm air to the main floor. Pumps are used to circulate water between the solar collectors and storage tank, and between the storage tank and the air handler. A fan is used to circulate warm air to the main floor from the air handler. Domestic hot water enters the tank at the bottom and leaves at the top. Auxiliary heat is provided by independent, idealized units located in the space heating loop (air-handling unit water supply) and at the outlet of the DHW tank.

Controllers in TRNSYS are used to operate the air-handler fan and pump in response to zone air temperatures computed by ESP-r and to operate the pump in the solar collector loop according to a classical control strategy (delta T between bottom of the tank and the solar collector outlet).

4.4.2 TRNSYS

Figure 4-12 shows the solar combi-system modeled in TRNSYS. The system is made up of four circuits: a solar circuit (green); a domestic hot water circuit (orange); an air loop (blue) and a water heating circuit (red).

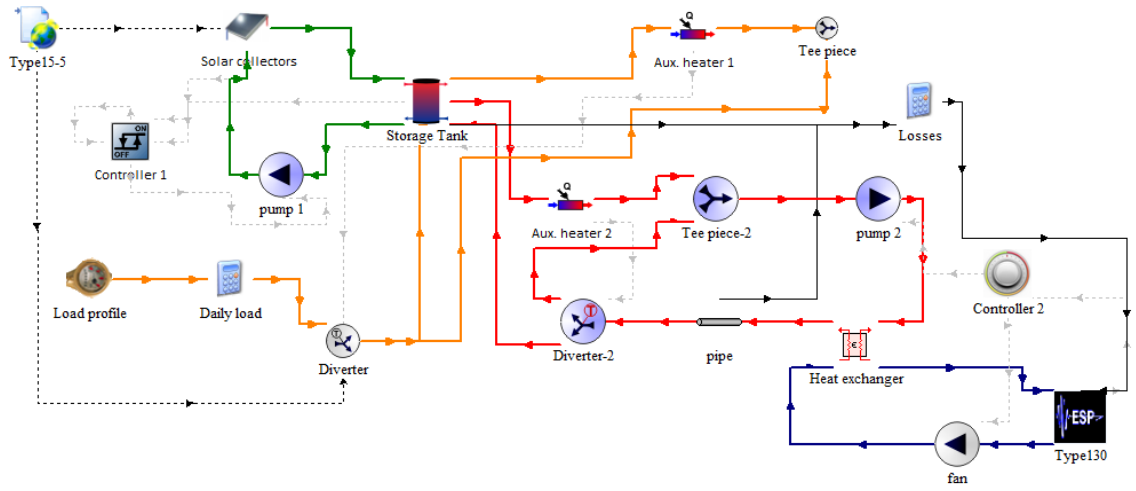


Figure 4-12 TRNSYS simulation for Test C

- **Solar collectors circuit**

The collectors are oriented to the south (azimuth angle = 0°) with a slope of 45°. The parameters used to describe the collectors are:

Table 4-5 Parameters of solar collectors

Tested flow rate	75	kg/hr.m^2
Intercept efficiency	0.811	-
Efficiency slope	2.710	W/(m^2.K)
Efficiency curvature	0.010	W/(m^2.K^2)
1st order IAM	0.072	-
2nd order IAM	0	-

The heat transfer fluid is a mix of water and glycol, with a specific heat of 3.6 kJ/kgK, and circulated at a flow rate of 200 kg/hr.

The stratified storage tank used to store the solar energy encompasses two immersed heat exchangers. Thermal losses (in kWh/day) from the storage tank are calculated using equation 1[2]:

$$Q_{loss} = 0.875 * 0.0525 * V^{2/3}$$

Where V = the volume of the tank in liters. This equation allows thermal losses to be adapted in a simple way when the tank volume is varied.

Pumps are turned on and off by a differential controller which compares the temperatures at the output of the solar collectors and with those in the tank, to prevent cooling the stored water when temperature in the solar circuit is lower than the temperature of the water in the tank.

- **Domestic hot water circuit (DHW)**

A daily load profile was used to simulate the consumption of domestic hot water. Figure 4-13 illustrates the hot water demand profile.

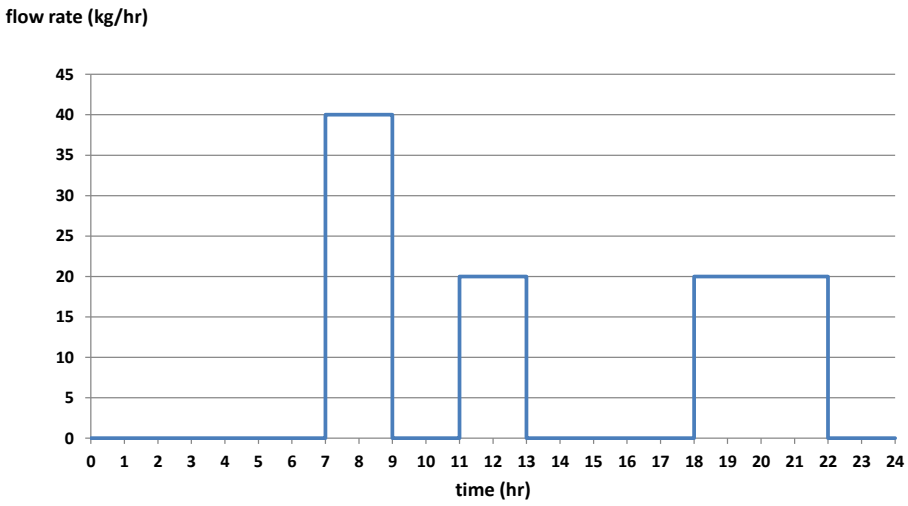


Figure 4-13 DHW load profile

[2] Category B of storage tank for a difference of temperature of 45°C with the outside of the tank , EU standard EN 15332 : 2007

Domestic hot water is supplied at 60°C. If the tank outlet temperature is lower than this, the auxiliary heater provides additional heat to reach the set point. If the tank outlet temperature is higher than 60 °C, the auxiliary heater is not used. A thermostatic valve brings the DHW supply temperature to 45 °C for distribution in the house (that thermostatic valve is modeled as a controlled diverter and a tee in TRNSYS).

- **Heating circuits**

The temperature set point for water supplied to the air handler is 60 °C. An auxiliary heater is used to reach the set point when required. If the temperature of the tank is higher than 60 °C, a three way valve is used to partially bypass the heat exchanger in the tank and recirculate water towards the air handler.

An on/off controller activates the pump depending on the temperature of the zone. The flow rate of the pump is 400 kg/hr.

A length of 10 meters of piping with a diameter of 0.02 m were also modeled for this loop. Their heat losses and those from the tank are all injected in the basement zone in the building.

On the load side of the water-air heat exchanger, warm air is circulated to the main floor. An ON/OFF controller is used to actuate the fan providing a flow rate of 1200 kg/hr of warm air when the temperature of the main floor falls below 20 °C. Both sides of the heating coil, source and load, are activated simultaneously by this controller. The dead band is 2 °C centered on 20 °C.

Type 130

For this demonstration Type 130 was configured with three zones (basement (zone 1), main floor (zone 2), and attic (zone3)), One air coupling port (ACCToTrnsys and ACCToEspr) and no hydronic coupling ports. Figure 4-14 represents the inputs/outputs connections of the Type.

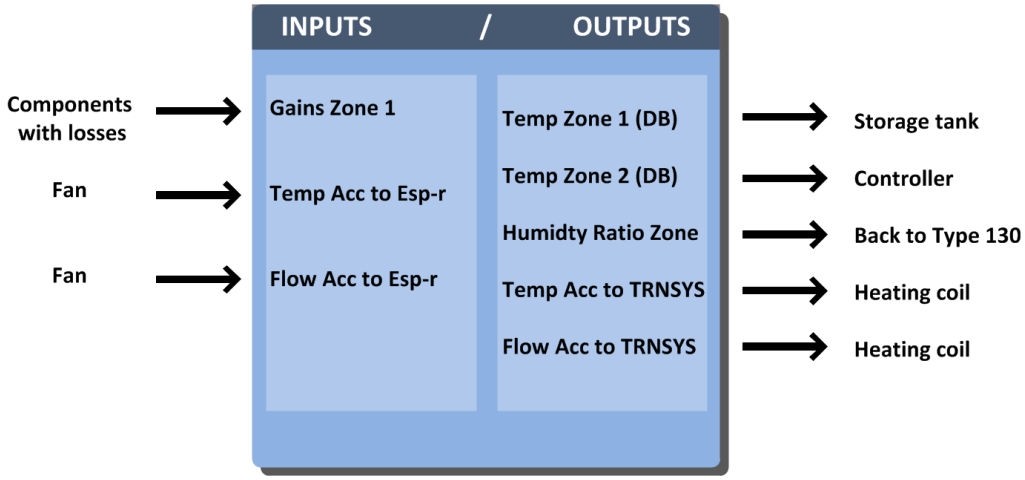


Figure 4-14 Type 130 connections

4.4.3 ESP-r

Figure 4-15 illustrates the model of the three zone building in ESP-r. The model is taken from the CCHT house (CCHT 2008) which comprises three thermal zones: basement; main floor and second floor; and attic space. The original model included an attached garage which was not modeled for this example.

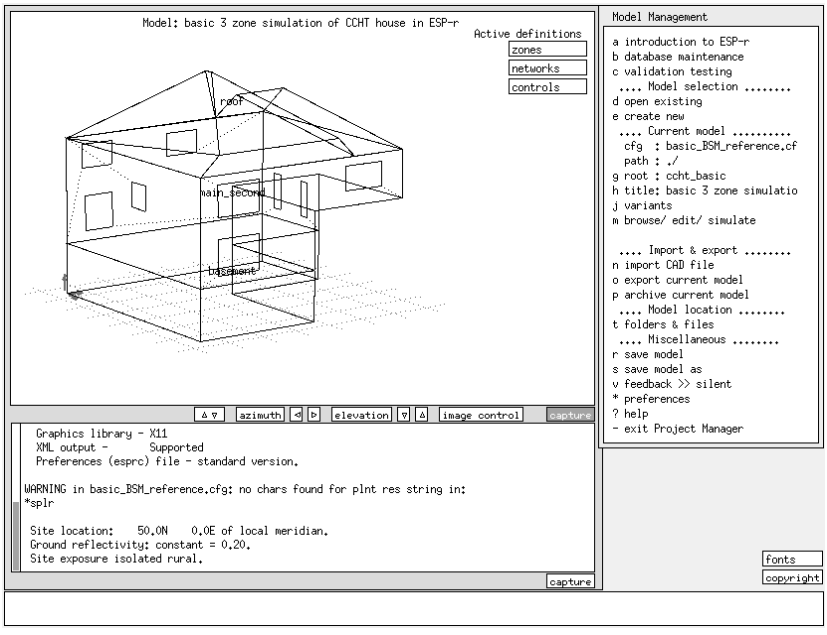


Figure 4-15 Zone house model in ESP-r

4.4.4 Coupling settings

The link between the two programs is maintained by the TRNSYS data exchange component, Type 130 and by two air-based coupling components, ACC_toESPr (responsible for data sent from TRNSYS to ESP-r) and ACC_toTrnsys (responsible for sending data from ESP-r to TRNSYS). Figure 4-16 shows how these components are connected with the whole simulation.

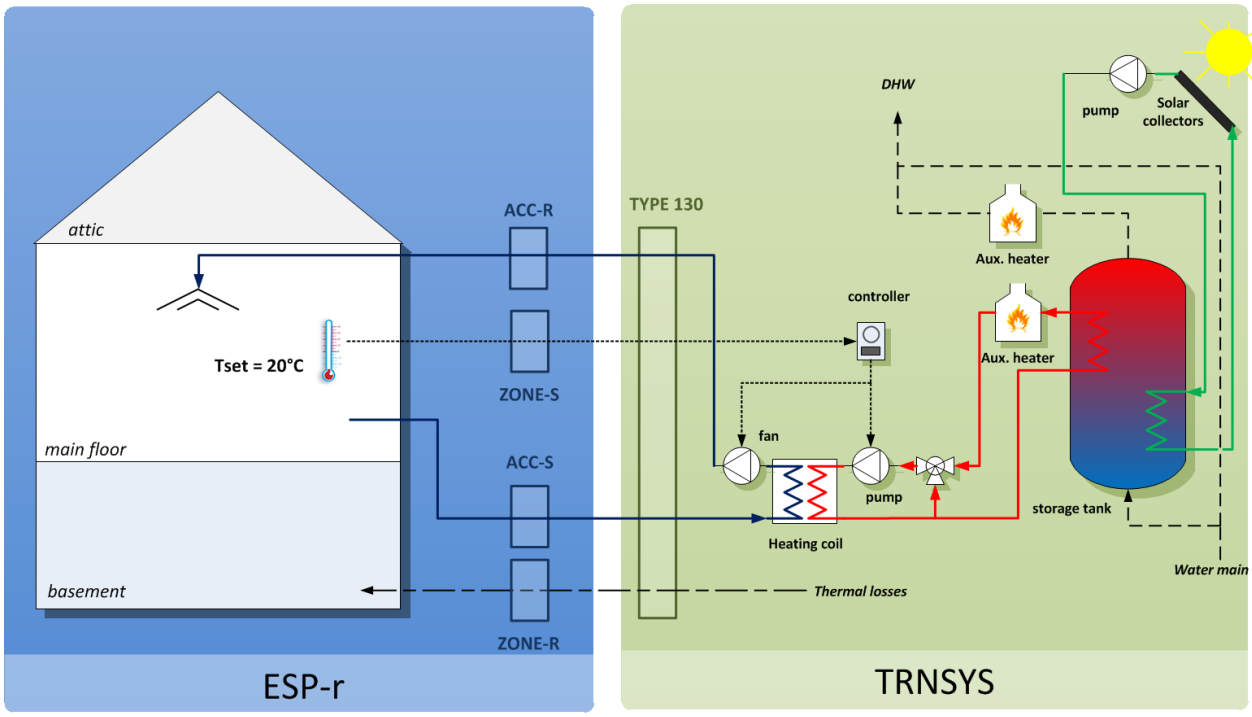


Figure 4-16 Connections at the interface between the two programs

The common simulation parameters (time step and weather data) in both programs were specified as follows:

Table 4-6 Co-simulation parameters for Test C

Duration of the simulation	1 year
Length of the startup period (ESP-r):	1 day
Length of the startup period (ESP-r):	1 minute
Weather data file	Toronto (CWEC)

4.4.5 Results analysis

- **Convergence**

The co-simulation runs until the end of the period (1 year) without any convergence issues; none of the TRNSYS components fail to converge at any time-step and ESP-r and the harmonizer attain convergence at every time-step. The number of invocations and iterations required to reach convergence are summarized below. Figure 4-17 illustrates the iterations per time-step over a section of the simulation period. As the plant network in ESP-r is very basic, and ESP-r does not perform iterations between the plant domain and the building domain, so the number of ESP-r iterations is equal to the number of invocations.

Table 4-7 Combi-system co-simulation results (annual simulation)

Simulation running time	16 min
Total number of invocations	1,069,150
Average number of invocations per time-step	2.04
Total number of ESP-r iterations	1,069,150
Total number of TRNSYS iterations	3,150,191
Average number of ESP-r iterations per time-step	2.04
Average number of TRNSYS iterations per time-step	6.01

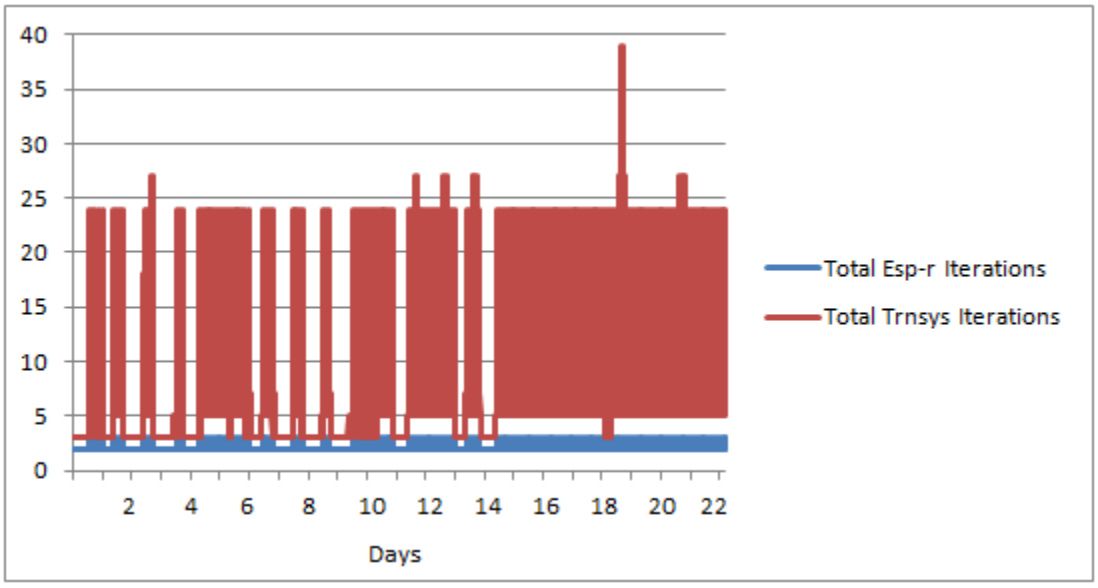


Figure 4-17 Number of iterations per time-step

Energy balances

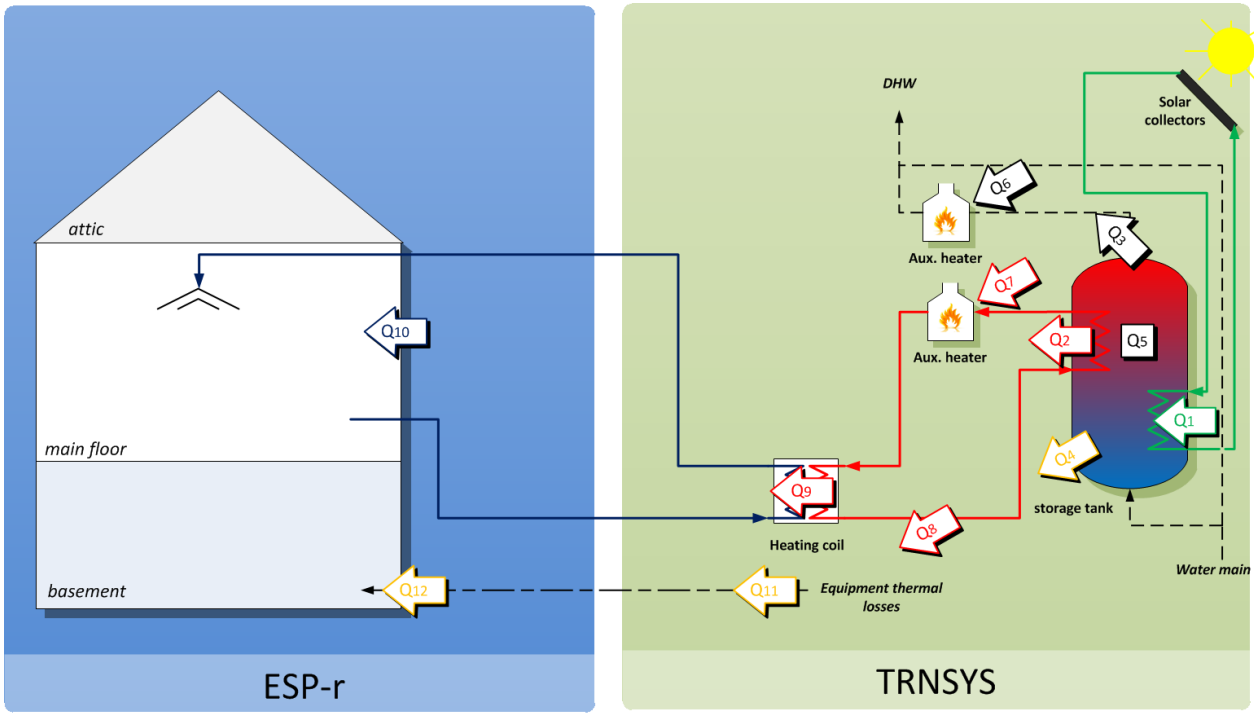


Figure 4-18 Energy transfers in the system

The following energy balances were performed to verify the results obtained from co-simulation. The data was derived from an annual simulation with a solar collector area of 10 m^2 and a tank size of 0.5 m^3. Figure 4-18 shows the energy quantities used in the thermal balance:

Table 4-8 Description of energy transfers

Q_1	*Energy from solar collectors entering the storage tank*	Q_7	*Energy from the auxiliary heater added to the water space heating loop*
Q_2	*Energy transferred from the tank to the water space heating loop*	Q_8	*Thermal energy losses of the pipes*
Q_3	*Energy transferred from the tank to the domestic hot water circuit*	Q_9	*Energy transferred from water space heating loop to the air*
Q_4	*Thermal energy losses of the storage tank*	Q_{10}	*Energy provided to the main floor zone*
Q_5	*Energy stored in the tank*	Q_{11}	*Total thermal energy losses of the equipment*
Q_6	*Energy from the auxiliary heater added to the domestic hot water circuit*	Q_{12}	*Energy entering the basement zone from the equipment thermal energy losses*

The purpose of each energy balance is to verify that the amount of energy entering the system is equal to the energy exiting and stored in the system. The error in the energy balance is calculated as follows:

$$\varepsilon = \frac{\sum Q_{IN} - \sum Q_{OUT}}{(\sum Q_{IN} + \sum Q_{OUT})/2}$$

With: $\sum Q_{IN}$ the sum of energy entering the system

$\sum Q_{OUT}$ the sum of energy exiting and stored by the system

Four energy balances were performed, one for each of the following energy systems: the storage tank; the water side of the space heating loop; the air side of the space heating loop; and for the

plant thermal losses. Only TRNSYS values are used in the storage tank and water space heating circuit. The air side of the space heating circuit and the plant thermal loss energy balances demonstrate the data exchange between the programs.

- *Storage tank*

$$Q_1 = Q_2 + Q_3 + Q_4 + Q_5$$

$$Q_1 = 3\ 891 \text{ kWh}$$

$$Q_2 + Q_3 + Q_4 + Q_5 = 1\ 335 + 2\ 528 + 11 + 14 = 3\ 887 \text{ kWh}$$

$$\varepsilon_{tank} = \frac{Q_1 - (Q_2 + Q_3 + Q_4 + Q_5)}{(Q_1 + Q_2 + Q_3 + Q_4 + Q_5)/2} = 0.094\ \%$$

- *Space heating loop (water)*

$$Q_2 + Q_7 = Q_8 + Q_9$$

$$Q_2 + Q_7 = 1\ 335 + 16\ 233 = 17\ 568 \text{ kWh}$$

$$Q_8 + Q_9 = 68 + 17\ 500 = 17\ 568 \text{ kWh}$$

$$\varepsilon_{heat\_water} = \frac{Q_2 + Q_7 - (Q_8 + Q_9)}{(Q_2 + Q_7 + Q_8 + Q_9)/2} = 0.002\ \%$$

- *Space heating loop (air)*

$$Q_9 = Q_{10}$$

$$Q_9 = 17\ 500 \text{ kWh}$$

$$Q_{10} = 17\ 419 \text{ kWh}$$

$$\varepsilon_{heat\_air} = \frac{Q_9 - Q_{10}}{(Q_9 + Q_{10})/2} = 0.0046\%$$

- *Equipment thermal losses*

$$Q_4 + Q_8 = Q_{11} = Q_{12}$$

$$Q_4 + Q_8 = Q_{11} = 11 + 68 = 79 \text{ kWh}$$

$$Q_{12} = 78.72 \text{ kWh}$$

$$\varepsilon_{thermal\ losses} = \frac{Q_{11} - Q_{12}}{(Q_{11} + Q_{12})/2} = 0.0034\%$$

Sensitivity of co-simulation results

Sensitivity analyses were performed to examine the sensitivity of the co-simulation results to the size of the storage tank and to the solar collector area. The net solar fraction has been used to compare the results; it quantifies the fraction of solar energy used in producing the domestic hot water and the warm water used in space heating.

$$f_{sol} = 1 - \frac{Q_{aux}}{Q_{tot}}$$

With Q_{aux} the energy consumed by the auxiliary heating system

Q_{tot} the total amount of energy needed from the solar collectors and from the auxiliary heater.

The graphs below show the evolution of the net solar fraction with the solar collector area for different ratios of storage volume per collector square meter (50, 75 and 100 L/m^2).

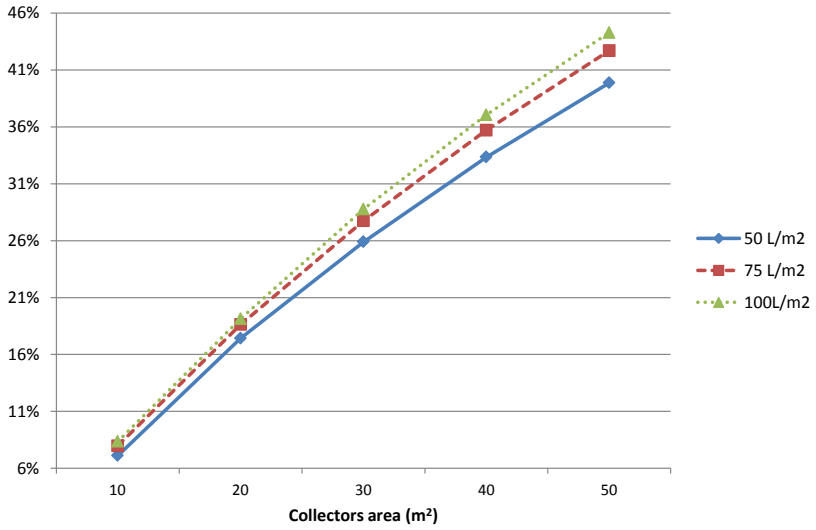


Figure 4-19 Space heating solar fraction

Figure 4-19 illustrates the solar fraction contributing to space heating and shows that solar energy contributes only modestly to the space heating of the house. Without a large area of collectors, the energy from the solar collectors used in heating the zone remains small. The system could be optimized to increase the solar fraction but the results show that the system behaves as expected. Increasing the number of collectors and the storage volume increases the solar energy collected and stored and thus reduces the auxiliary heating energy.

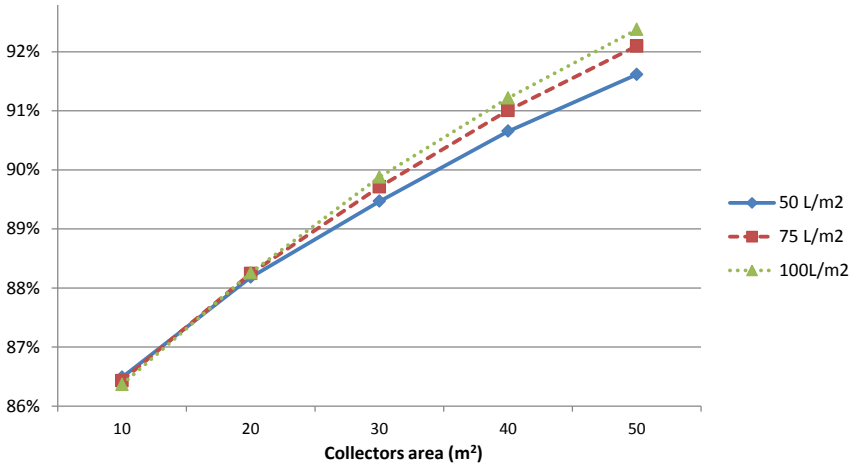


Figure 4-20 Domestic hot water solar fraction

The same trend can be seen in the results for the solar fraction contributing to the domestic hot water (DHW) heating, as illustrated in Figure 4-20. With the DHW the solar fraction is higher and energy collected from the sun is almost enough to heat the water on its own. Even with a 10 m^2 collector area, auxiliary heating required rarely exceeds 14 %.

Figure 4-21 shows the global solar fraction of the combi-system.

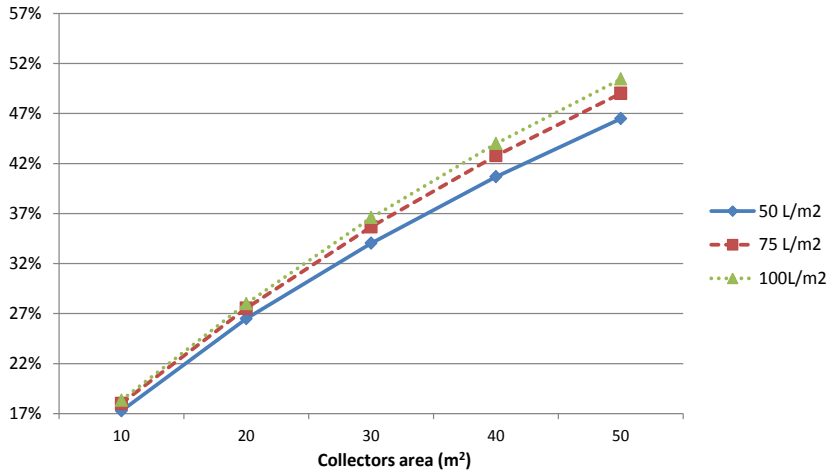


Figure 4-21 System total solar fraction

The results presented in this section demonstrate that the runtime coupling functions as intended and that it provides a useful tool in the analysis of NZEBs.

The coupling has enabled the following data exchanges:

- flow, temperature and humidity data computed by a network of TRNSYS types onto an ESP-r plant network (in this case air exiting the air handling unit and entering the building)
- flow and temperature data computed by an ESP-r plant network as boundary conditions on a network of TRNSYS types (in this case return air from the building to the air handling unit)
- temperature and humidity conditions within the building as boundary conditions on the TRNSYS network (in this case environment conditions for tank and piping)

- heat transfers from TRNSYS networks as boundary conditions (including internal gains) within ESP-r's building envelope model (in this case thermal losses from the tank and pipes injected into the basement)

The simulation converges and energy balances have been verified. The results obtained by co-simulation correspond to the trends that were expected for the modeled solar combi-system and house.

CHAPTER 5 USING THE ESP-R / TRNSYS CO-SIMULATOR

This last chapter is describing how to perform co-simulations from a user perspective. The creation of the input file for the coupled programs and for the Harmonizer will be presented. Then, we will show how to run a co-simulation and how to collect the results.

This chapter essentially contains the same information as the "getting started" user guide that is distributed with the Harmonizer as part of the ESP-r and TRNSYS packages. The TRNSYS-specific instructions were written by the author of this thesis, while the instruction specific to ESP-r were authored by the Carleton University team.

5.1 Generalities

One of the main objectives in the design of the co-simulator was to minimize modifications to the existing programs. In comparison to a standard simulation with only one program, the same external simulation files are used in a co-simulation. Users who are already familiar with both programs should have no problems following the procedure for coupled simulations. Figure 5-1 lists the external files involved in a co-simulation.

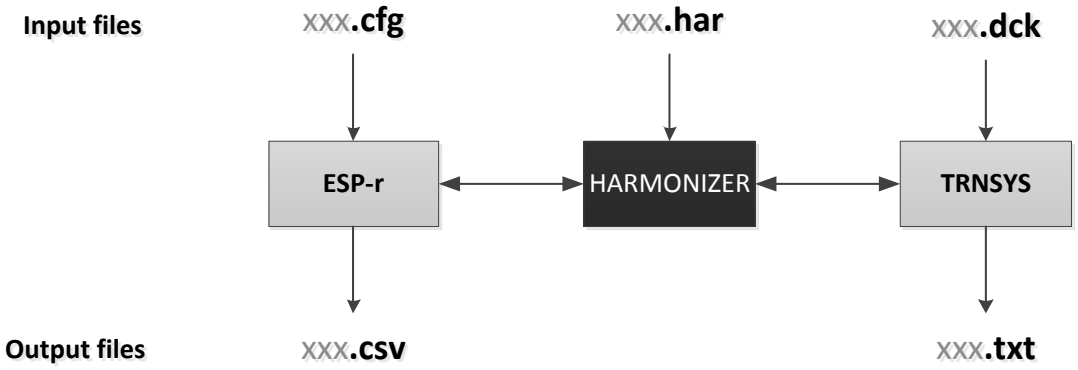


Figure 5-1 Co-simulator's input and output files

On the ESP-r side, an input file with the ".cfg" standard ESP-r input file format is required, as well as the associated directories and files describing the entire ESP-r project. The user can either create the model from the Project Manager interface or by editing the input file. The same principle applies to TRNSYS, where the deck file includes the complete model description,

whether performing a TRNSYS-only or a coupled simulation. Output files can be generated by both programs as they are for standard ("one-program") simulations. A standard ".csv" output file can be defined and configured in ESP-r. In TRNSYS, all standard output components can be used (printers, simulation summaries, etc.). A new, co-simulation specific input file is required for the Harmonizer. This Harmonizer input file specifies co-simulation parameters.

5.2 Harmonizer input file

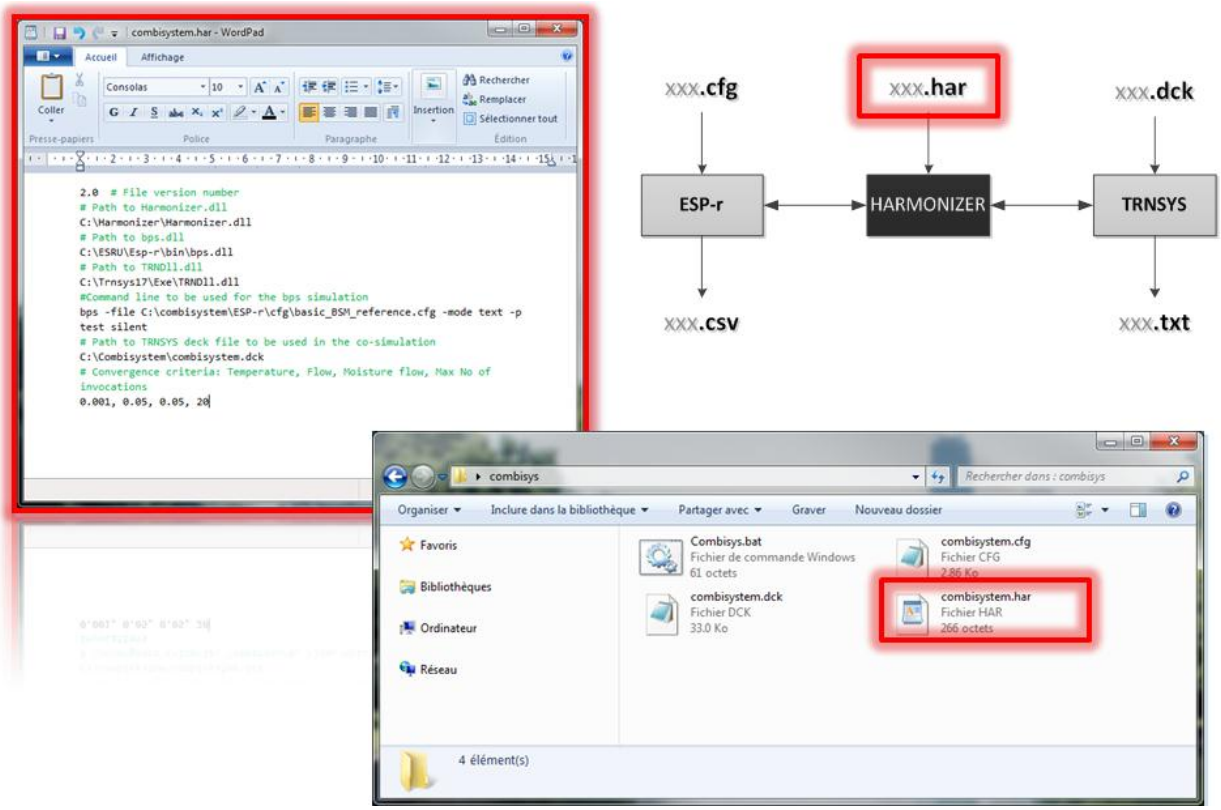


Figure 5-2 Harmonizer input file

The Harmonizer input file indicates to the Harmonizer launcher where to find every program's DLL and some information about a specific co-simulation. The first lines specify the path to TRNSYS, ESP-r and the Harmonizer DLL. This ensures that co-simulations can be performed with both programs installed in user-specific locations, as long as both programs were installed properly and that the main ESP-r and TRNSYS DLL's are capable of finding their own

secondary files. Then, paths to the ESP-r (.cfg) and TRNSYS (.dck) model files are specified. Finally, four convergence criteria can be specified by the user: temperature, fluid flow rate, moisture flow rate and the maximum number of invocations per time-step. The temperature change criterion is an absolute value in °C, while the two flow rate change criteria are relative values in % (that revert to absolute change if the flowrate is close to 0). That last line is optional. If it is not present, default values are used: 0.001°C for the temperature, 0.05% for flow rates and the number of invocations is limited to 20 per time step.

An example of Harmonizer input file with user-specified convergence criteria is given below:

```
2.0  # File version number
# Path to Harmonizer.dll
C:\Harmonizer\Harmonizer.dll
# Path to bps.dll
C:\ESRU\Esp-r\bin\bps.dll
# Path to TRNDll.dll
C:\Trnsys17\Exe\TRNDll.dll
#Command line to be used for the bps simulation
bps -file C:\path_to_ESP-r_model\cfg\cfgfile.cfg -mode text -p test silent
# Path to TRNSYS deck file to be used in the co-simulation
C:\Path_to_deck_file\deck_file_name.dck
# Convergence criteria: Temperature, Flow, Moisture flow, Max No of invocations
0.001, 0.05, 0.05, 20
```

5.3 ESP-r model

An ESP-r co-simulation model is created as a traditional model using ESP-r only. The only difference is the addition of the coupling components in the plant domain. The different steps to create a model for a co-simulation are detailed below. It is assumed that the building is already modeled and only the configuration of the coupling components will be described.

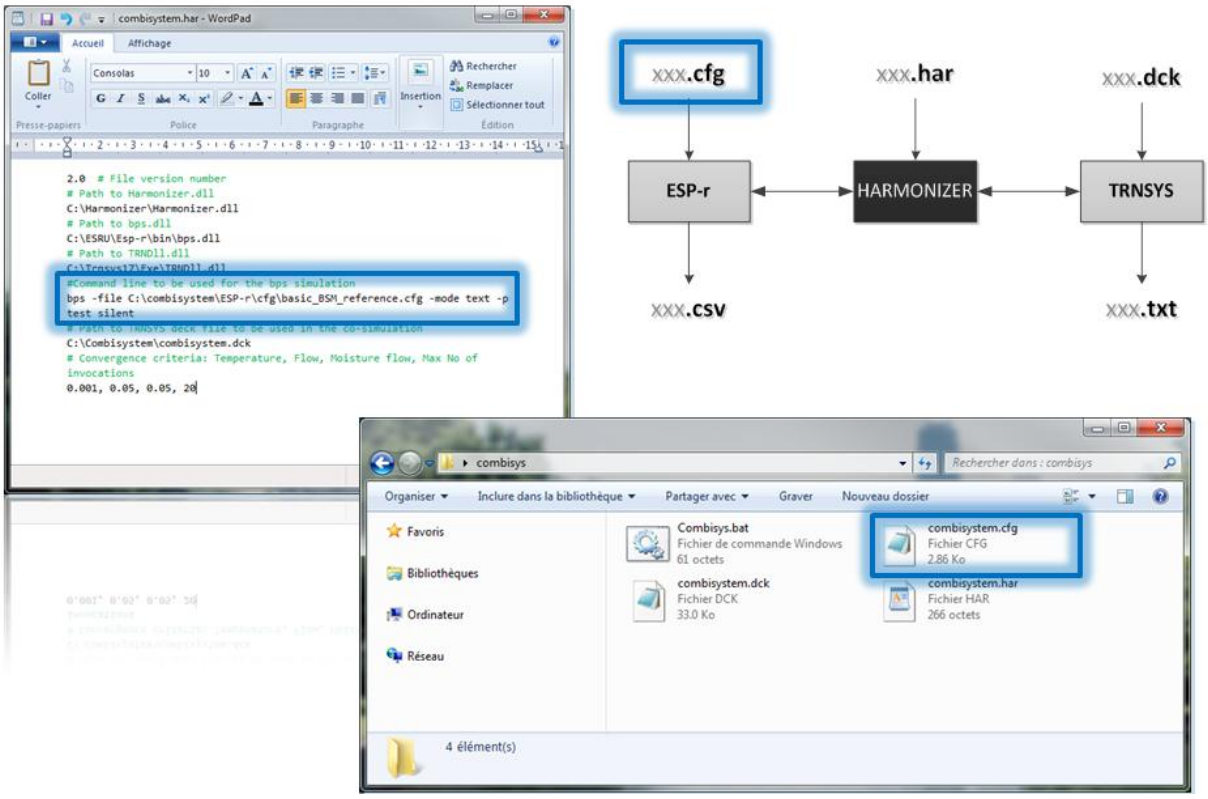


Figure 5-3 ESP-r input file

1. Create a plant system

Starting from the Project Manager main window:

- Select option *m: /browse/edit/simulate*
- Select option *d: plant & systems*
- Select option *b: Explicit (plant network)*
- Create a plant network *(yes)*
- Proceed with network description *(yes)*
- Select database *plantc.db1* (should be default)

2. Add coupling components

In the plant definition window:

- Select option *d: Components*
- Add component
- Select option *d: Solar and others*
- Select the components you require and give them a meaningful name. The index of the component is used if you wish to change the order in which components are linked to TRNSYS. Figure 5-4 shows the addition of two HCC and two ACC (sending and receiving) components together with a radiator.

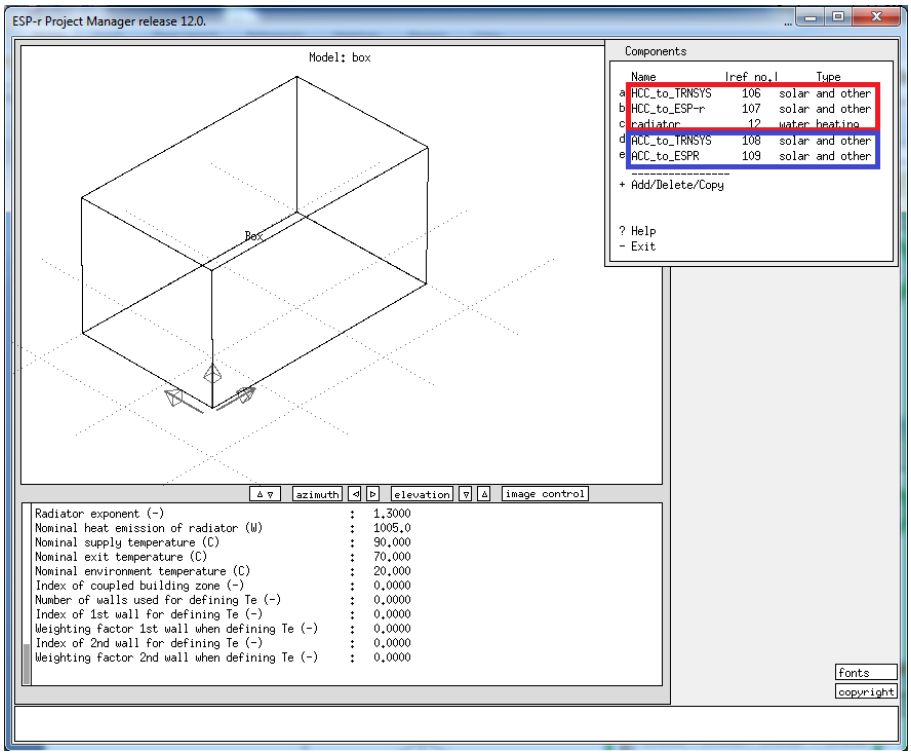


Figure 5-4 Example of a plant system including coupling components

3. Configure the connections

In the plant definition window:

- Select option *e: Connections and add the required connections to connect the components.*

There are two different cases depending on the nature of the exchanged fluid. If the coupling components are Hydronic Coupling Components, they have to be connected to at least one other component of the plant. In the case of Air Coupling Components, they need to be linked to a thermal zone. Schematics of these connections are presented in Figure 5-5. In both cases, a connection has to be defined between the two Coupling Components of one fluid connection to TRNSYS (sending and receiving).

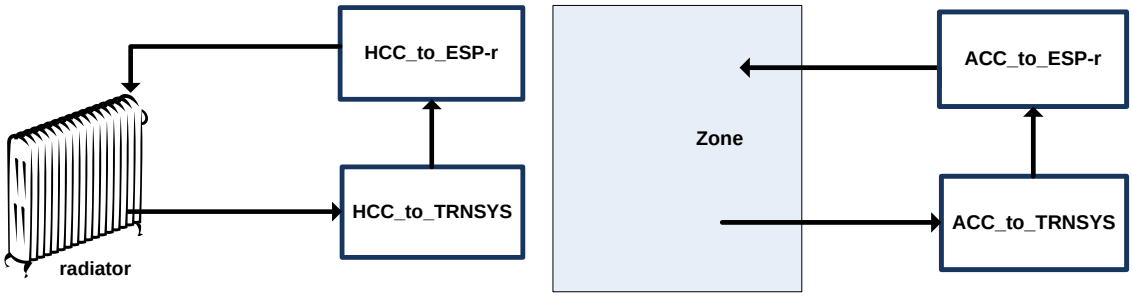


Figure 5-5 Coupling components connections: HCC on the left and ACC on the right (Macdonald, 2012)

The corresponding connections to the previous example of HCC and ACC in the Project manager is shown in Figure 5-6.

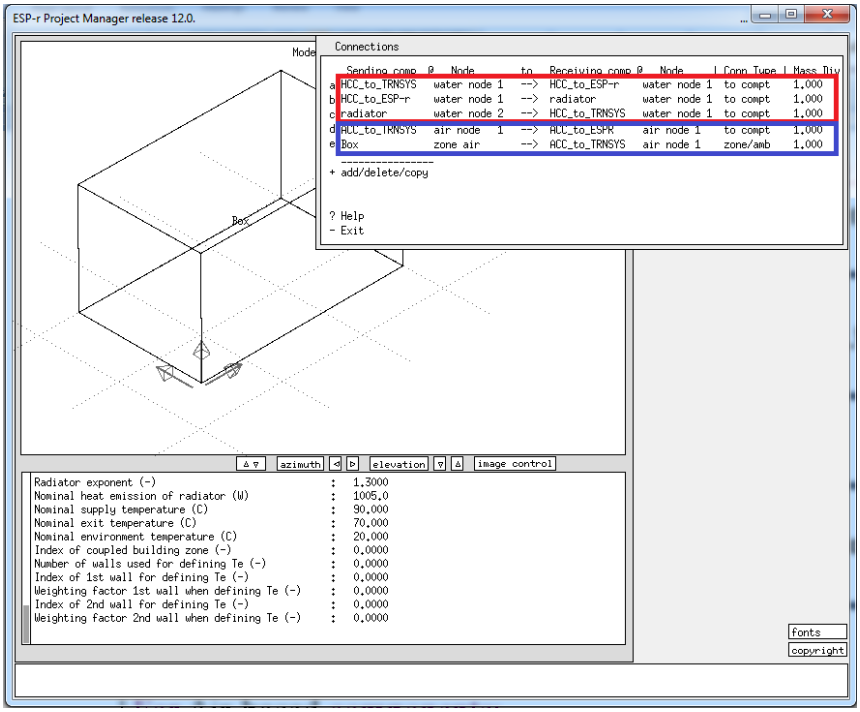


Figure 5-6 Example of connections for ACCs (blue) and HCCs (red)

4. Define the simulation preset

The preset is what is used to define the simulation parameters. From the Browse/Edit/Simulate menu:

- Select option *r: simulation*
- Select option *a: simulation presets*

The start-up period, simulation dates and time-steps are defined here. The co-simulation Design Team recommends that ESP-r plant time-step should always be equal the zone time-step, and the results save level should be set to 5 to get the xml output.

5.4 TRNSYS model

5.4.1 Creation of TRNSYS input file

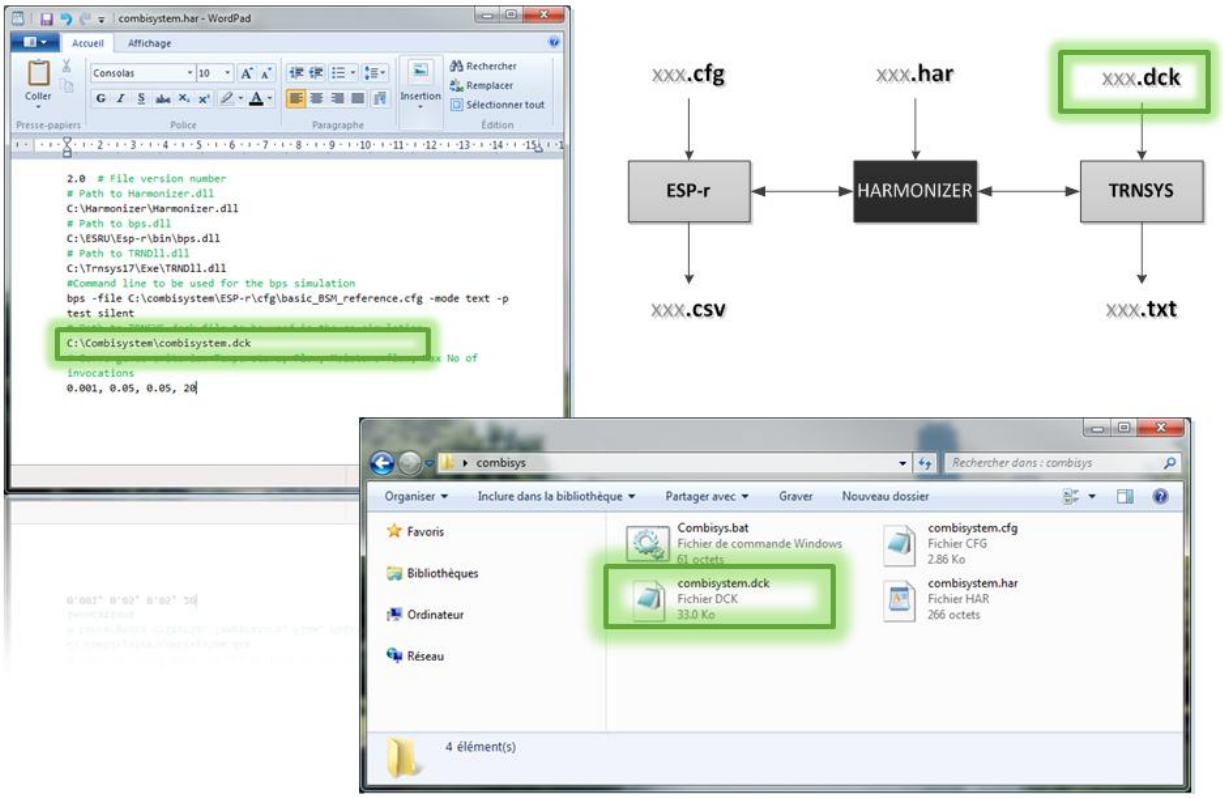


Figure 5-7 TRNSYS input file

1. Create the system network

The example below (Figure 5-8) shows the system network for a combi-system providing heat to a building through the air-handling unit (heat exchanger in that model).

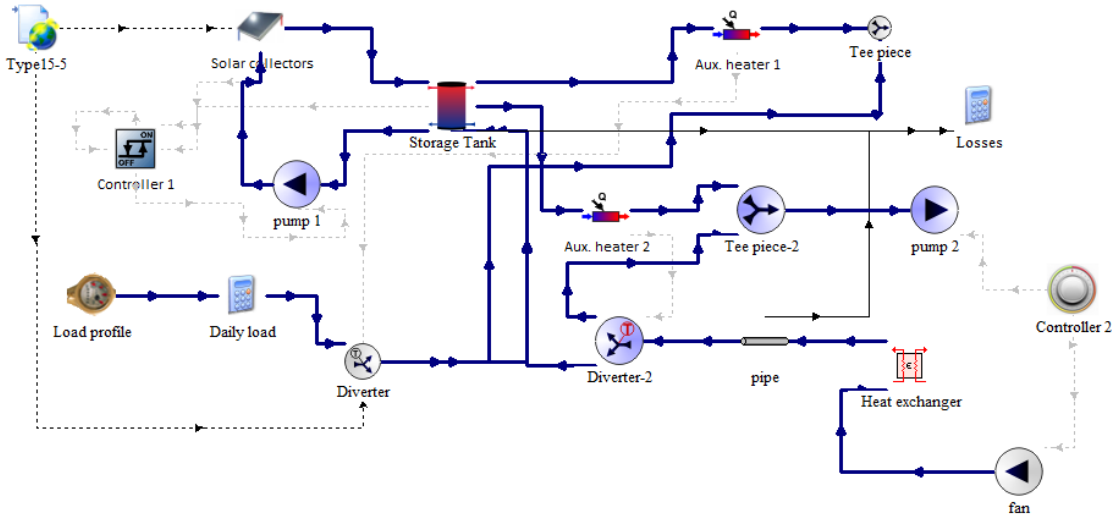


Figure 5-8 TRNSYS network of Types

2. Add Type 130 to the project

Type 130 is added to the project by selecting the component in the list of Types and dragging it to the Assembly window.

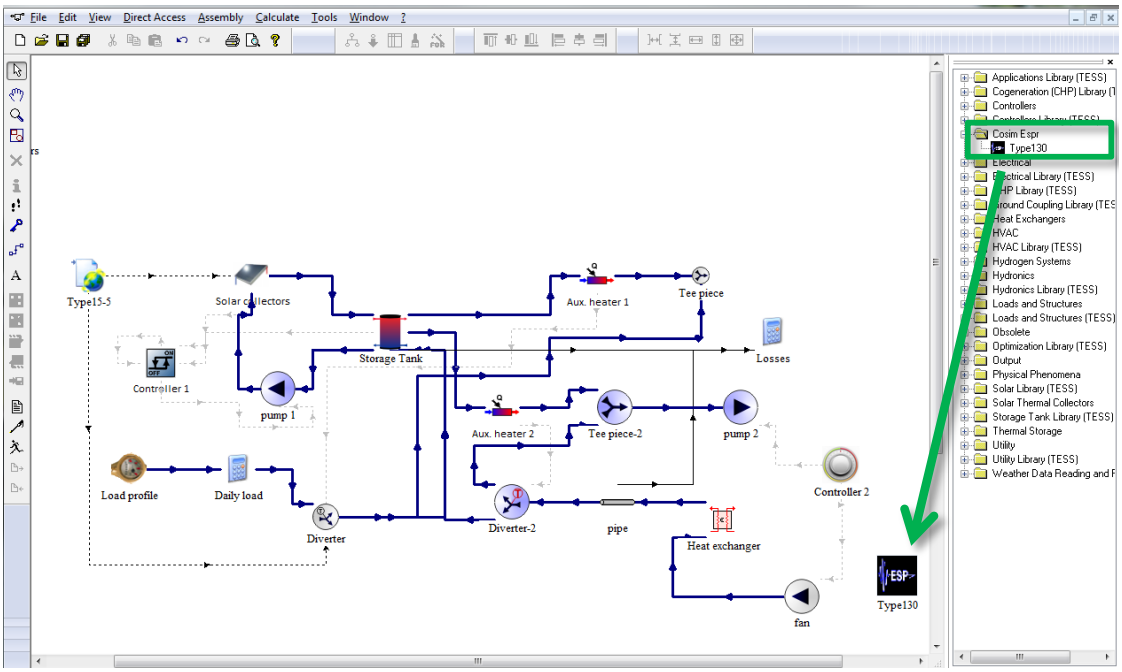


Figure 5-9 Addition of Type 130 to the network of Types

3. Define the number of zones, ACCs, and HCCs components in Type 130 parameters

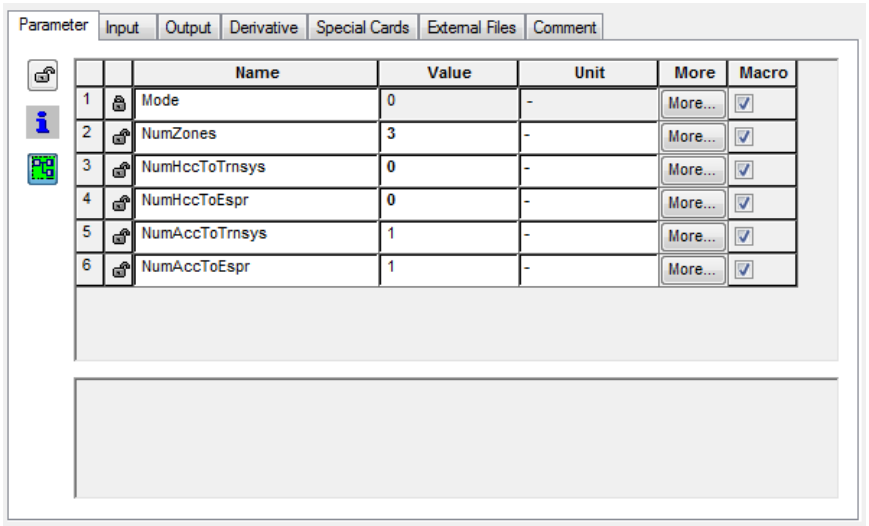


Figure 5-10 Type 130 parameters settings

ACCs, HCCs and zones must be defined in the same order as in ESP-r. This particular example uses one ACC To TRNSYS (inlet of the fan) and one ACC To ESP-r (outlet of the secondary side of the heat exchanger).

4. Connect Type 130 inputs and outputs to the other components

The connections between Type 130 and the other components are presented in red in Figure 5-11. The ACC To TRNSYS data (flowrate, temperature and humidity available as outputs from Type 130) is connected to the matching fan inputs. Outlet conditions from the heat exchanger are connected to the ACC to Esp-r (Type 130 inputs). The basement zone temperature calculated by Esp-r (available as an output of Type 130) is connected to the storage tank environment temperature. The main floor temperature is connected to the thermostat. Finally, thermal losses from the tank and pipes are connected to the input of Type 130 representing casual gains for the basement zone.

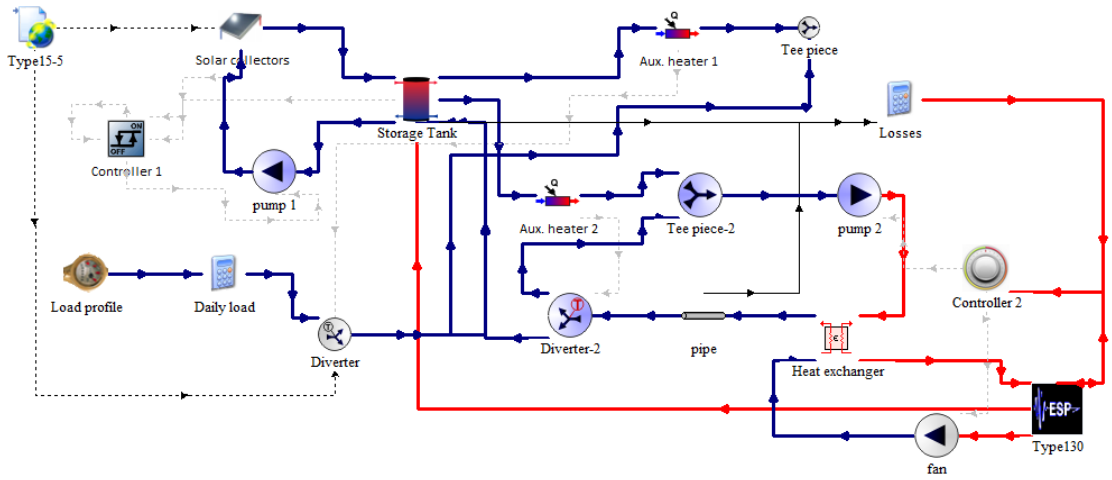


Figure 5-11 TRNSYS network of Types with Type 130

5. Define the same time-step and simulation start and stop time

These parameters are defined in the control card windows. They have to be the same as those defined in ESP_r. Special care must be taken to take the ESP-r startup period into account (refer to section 5.5.1 for more details).

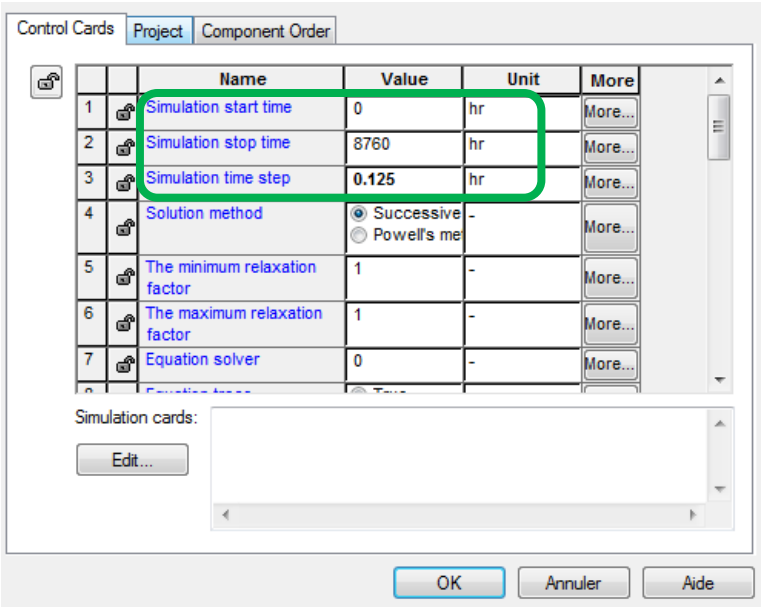


Figure 5-12 Simulation parameters

6. Create the .dck file and save the Studio file (.tpf)

The deck file is created by selecting Calculate/Create input file or by clicking on the pen icon in the Simulation Studio window. Unlike the deck file, the Studio file (.tpf) is not necessary to run the co-simulation but it is worth saving it to be able to re-open it later and modify it in the Simulation Studio.

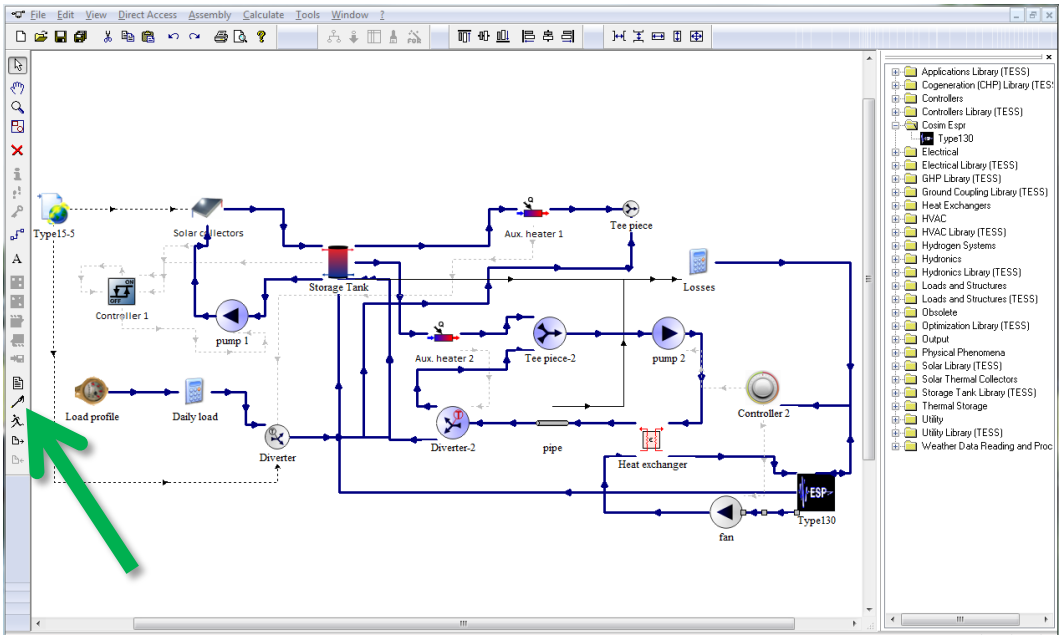


Figure 5-13 Creation of TRNSYS input file

5.4.2 Type 130 Test mode

Before running a co-simulation with ESP-r, it is possible to test and debug the TRNSYS part by activating the test mode of Type 130. This enables exchanging data with a test-mode version of the Harmonizer DLL. This test-mode DLL sends constant values to a maximum of 2 zones, 2 HCCs and 2 ACCs. Results obtained using the test mode are not realistic but can be useful in testing the system created and identifying errors on the TRNSYS-side of the simulation more easily.

Another functionality allowed by this mode is to set the number of minimum iterations of components linked to the Harmonizer. A new parameter appears in Type 130 proforma: NumIterations which defines this number of forced iterations. This was developed in order to simulate the action of the real Harmonizer which may invoke some types many times per time step. Again, this capability can be used to debug the TRNSYS-side of the simulation (e.g. user-created components) to make sure the extra iterations that will likely result from the co-simulation do not have undesired side effects.

1. Define the parameter Mode = 1

2. Choose the number of forced iterations (the minimum is one, which means no forced iterations). All types connected to a Type 130 output will be forced to iterate this number of times.

3. Save the project (.tpf)

4. Run the simulation directly from the Studio

5. Constant values sent by Type 130 in test mode:

Table 5-1 Constant values sent by Type 130 in test mode

Zone 1	Temperature	21	°C
	Humidity Ratio	0.006	-
Zone 2	Temperature	22	°C
	Humidity Ratio	0.007	-
HCC 1	Temperature	31	°C
	Flow-rate	101	kg/hr
HCC 1	Temperature	32	°C
	Flow-rate	102	kg/hr
ACC 1	Temperature	41	°C
	Humidity Ratio	0.0004975	-
	Flow-rate	201	kg/hr
ACC 2	Temperature	42	°C
	Humidity Ratio	0.0004950	-
	Flow-rate	202	kg/hr

5.4.3 Note about controllers

Running a co-simulation increases the total number of iterations per time-step in TRNSYS due to the multiple invocations. It is advised to increase the default value of the maximal number of iteration allowed in the deck file. Indeed, the initial value fits with a simulation using TRNSYS only. Modifying the parameter prevents the simulation to stop with a convergence error message while the actual reason is that co-simulation necessitates more iterations than a standard simulation.

Some Types such as controller Type 2 (ON/OFF controller, standard library) and a series of similar controllers in the TESS libraries (aquastat, humidistat, multi-stage controller, etc.) may be affected by a large number of iteration in a time-step. These Types sense a variable (e.g: temperature, humidity, etc,) and depending on its value send a corresponding control signal. At each iteration, the output of the controller may change if the value of the sensed variable is different. In order to prevent non convergence issues the number of oscillations for the controller within a time step is limited. These types either count the number of times they were called or the number of oscillations (discrete change in the output signal) within a time step, and if that number exceeds a threshold set by the user they "stick" to their value. Co-simulation may include a significant number of iterations resulting from successive invocations and not from oscillations within TRNSYS. In such a case, after few (or even one) invocations these Types would "stick" to their values before even performing one oscillation in a given invocation.

To prevent this type of issue, new functions that inform Types about the number of invocations and the number of iteration per invocation were created. They are presented above in section 3.2.4. It is recommended to modify the source code of Types that use the principle of "sticking" to a value after a given number of iterations or oscillations. Instead of basing the oscillations limitation on the total number of iterations or the total number of oscillations within a time step, they should reset the number of counted iterations or oscillations to zero at each new invocation. An example of changes needed for Type 2 is given in ANNEX 2.

5.5 Co-simulation

Once the TRNSYS and ESP-r model files have been defined, the co-simulation is ready to run. The following instructions describe how to proceed to launch a co-simulation and recover the results.

5.5.1 Running a co-simulation

It is important to first ensure that the simulation periods in TRNSYS and ESP-r are the same (i.e. same start and end days and same number of time-steps per hour). If a climate file is used in TRNSYS, users should also make sure it matches the weather data used in ESP-r.

Unlike TRNSYS, ESP-r begins simulating with a specified startup period and this needs to be calculated when defining the TRNSYS start time. As an example, an hourly simulation from start = 0 to stop = 8760 in TRNSYS would match a simulation from the 2nd of January to the 31st of December in ESP-r with a one-day startup period. If the ESP-r simulation starts on the 1st of January, the start-up period in ESP-r actually represents the last hours or days of the previous year. In TRNSYS, a start time = 0 always represents January first at 0:00 AM, and negative time values are not possible. The solution in such a case is to start the TRNSYS simulation at a time a few hours or day before the end of the first year, and finish it after the second year. For an annual ESP-r simulation starting on January 1st with a 14 day start-up period, the TRNSYS start time would be 8424 and the stop time 17520.

The co-simulation can be launched from the Windows command prompt, a MinGW or Cygwin window. For the three cases, the Harmonizer is invoked from the directory containing the Harmonizer input file by entering the absolute path to the Harmonizer executable program following by the name of the Harmonizer input file.

E.g. : *C:/Harmonizer-install-directory/harmonizer.exe my_model.har*

5.5.2 Results recovery

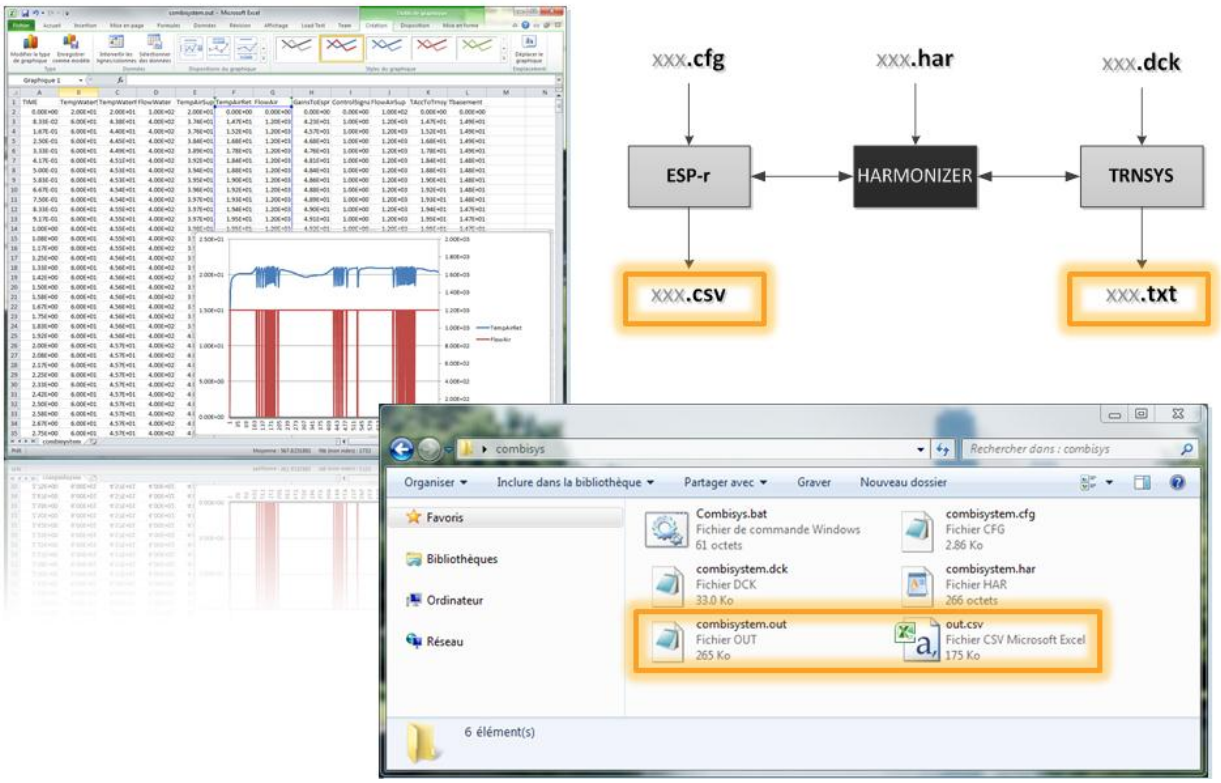


Figure 5-14 Co-simulation output files

The procedure to specify output files in ESP-r and TRNSYS is the same within each program as for "one-program" simulations.

ESP-r

ESP-r will produce a .csv file (in the cfg directory) with data as specified in the input.xml file which should be located in the /cfg directory. Two example input.xml files are provided here. The first output specific data only, including zone air point temperatures and humidities as well as all the data passed between ESP-r and TRNSYS.

```
<?xml version="1.0" encoding="UTF-8"?>
<configuration>
  <apply_style_sheet>false</apply_style_sheet>
  <dump_all_data>false</dump_all_data>
  <enable_xml_wildcards>true</enable_xml_wildcards>
  <hierarchy>flat</hierarchy>
  <link_style_sheet>false</link_style_sheet>
```

```
  <output_dictionary>true</output_dictionary>
  <report_startup_period_data>false</report_startup_period_data>

  <step_variable>building/time_step</step_variable>
  <step_variable>climate/dry_bulb_temperature</step_variable>
  <step_variable>building/zone*/air_point/temperature</step_variable>
  <step_variable>building/zone*/air_point/relative_humidity</step_variable>
  <step_variable>plant/co-sim/*</step_variable>
</configuration>
```

The second dumps out all the data used in the ESP-r calculations.

```
<?xml version="1.0" encoding="UTF-8"?>
<configuration>
 <hierarchy>tree</hierarchy>
 <dump_all_data>true</dump_all_data>
 <time_step_averaging>false</time_step_averaging>
</configuration>
```

TRNSYS

Output components such as Type 25 (printer) or Type 46 (printegrator) have to be part of the TRNSYS model in order to save results from the simulation. Online plotter Type 65 can be used in the mode that creates an output file but it will not produce any plot on the screen during the simulation. All TRNSYS output files are created by default in the directory that contains the deck file. Otherwise, users can specify where the results are saved for each component that creates a results file. The usual .log and .lst files summarizing the TRNSYS simulation, warnings and errors are also automatically generated in co-simulations

CONCLUSION

A run-time coupling between TRNSYS and ESP-r was implemented in order to combine their strengths in analysing specific domains of advanced low-energy buildings such as net-zero energy homes with on-site renewable energy systems.

The project was carried out by a Design Team consisting of researchers at Carleton University, an industry expert at Thermal Energy Systems Specialists (TESS), a project manager at Natural Resources Canada, and the École Polytechnique team (author of this MASc thesis and his supervisor). The author of this Master Thesis was the lead developer for the TRNSYS-side of the project and, as a member of the Design Team, was involved in all the other tasks reported here.

The co-simulator implements a "strong" coupling between the two programs, where both programs perform internal iterations (inside each program) within an overall (co-simulation) iteration loop at each time step. It is the first time this technique is successfully implemented between ESP-r and TRNSYS and, according to our literature survey, between similarly complex Building Performance Simulation (BPS) programs.

The selected approach minimized changes to the existing source codes to ensure maintainability of the co-simulator as both programs evolve through their development cycles. New components that receive and pass data to the other program were implemented in the two software programs. A multi-DLL structure enables the coupling and exchange of information. A third piece of software, the Harmonizer, was also created. Its role is to manage the exchange of data, the marching through time of the two programs and the convergence handling.

In TRNSYS, the modifications include the addition of a new category of components, the Data Exchanger Types. A component of this category, Type 130, was created specifically for the coupling with ESP-r. More than exchanging data traditionally with other Types in a TRNSYS network of components, it also communicates with the Harmonizer. Type 130 provides and passes information to ESP-r and TRNSYS. It is also able to force the TRNSYS kernel to continue iterating if TRNSYS has converged but co-simulation convergences requires more iterations.

Basic data exchange test cases were implemented successfully to validate the data exchange method and the coupling strategy. The co-simulator allows the simulation of a system implemented in TRNSYS that controls air conditions (temperature, humidity) of a building

modeled in ESP-r. A more complete simulation example modeling a solar thermal combi-system was developed and implemented. The results show that the co-simulation approach can be used for similar problems. Results were deemed to be representative of the simulated system by the Design Team. Energy balances within each program and between the two programs were verified.

Users with some knowledge of both programs will be familiar with the steps required to perform a co-simulation. The definition of the two parts of the system in each program is based on the traditional way of implementing a simulation: inputs files are unchanged, coupling components are implemented as standard components and the result recovery process stay the same for the two programs. Setting the co-simulation parameters in the Harmonizer input file is the only specific task required to run a coupled simulation.

The co-simulator is currently distributed with the release versions of both TRNSYS, (since version 17 01.0024) and ESP-r. Future work on the project could include an extension of the coupling to ESP-r electrical domain. The development of redistributable TRNSYS applications, known as TRNSED executables, could be also recommended in order to make the co-simulator available to users who do not possess a TRNSYS license.

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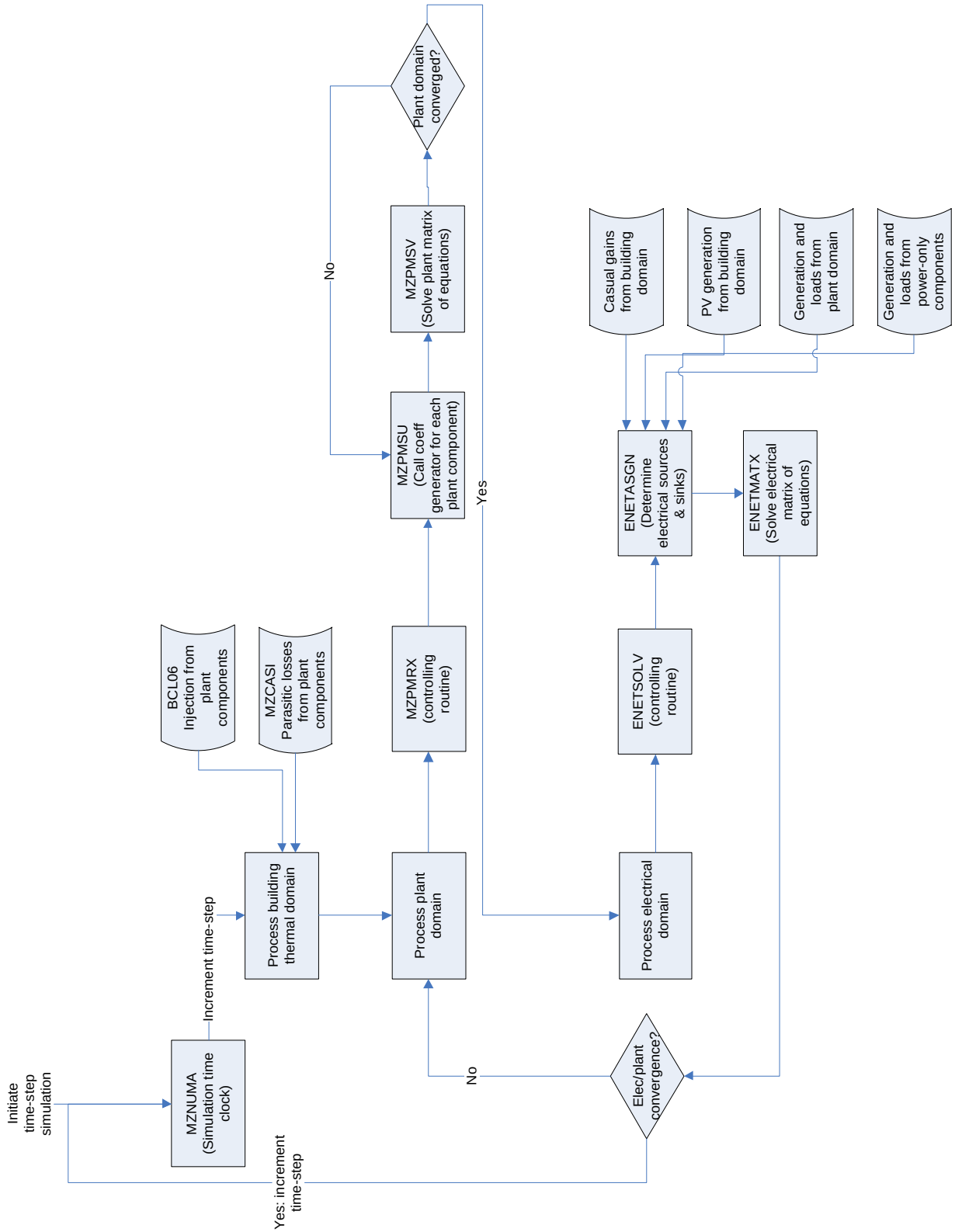
ANNEX 1 – ESP-R METHODOLOGIES



(Beausoleil-Morrison, 2011)

ANNEX 2 – SOURCE CODE MODIFICATIONS IN TRNSYS

Subroutine	Modifications	Code
TrnsysData	Create Call7	**Logical** :: Call7(nMaxUnits) **Data** Call7/nMaxUnits*.false./
	Add the logical variable "CosimConvergenceChecking Time"	**Logical** :: CosimConvergenceCheckingTime = .false.
	Add external program convergence flag	!Variable to check if an external program has converged **logical** :: CosimConv = .true.

TrnsysFunctions	Allow Info(9) to be equal to 6 in "SetIterationMode(i)"	**Subroutine** SetIterationMode(i)
		!Export this subroutine for its use in external DLLs.
		!Dec$Attributes DLLexport::SetIterationMode
		Use TrnsysConstants
		Use TrnsysFunctions
		Use TrnsysData, **Only**: CurrentUnit,CurrentType,Info
		Implicit None
		Integer i
		If ((i < 0) .or. (i > 6)) **Then**
		Call Messages(138,' ','Fatal',CurrentUnit,CurrentType)
		Else
		Info(9,CurrentUnit) = i
		Endif
		End Subroutine SetIterationMode

	Add function "getIsCosimConvergenceChec kingTime"	! getIsCosimConvergenceCheckingTime **Function** getIsCosimConvergenceCheckingTime() **!dec$ attributes dllexport :: getIsCosimConvergenceCheckingTime** **Use** TrnsysData, **Only**: CosimConvergenceCheckingTime **Implicit None** **Integer** getIsCosimConvergenceCheckingTime

		getIsCosimConvergenceCheckingTime = CosimConvergenceCheckingTime **End Function** getIsCosimConvergenceCheckingTime
TRNSYS	Add the flag CosimConv in initialization	**Use** TrnsysData, **Only**: [...], CosimConv

	Add a call to Exec at the end of the loop to call data exchanger Types
	Check overall convergence
	Force new iterations if CosimConvergence = false
		If (ict /= 0) **Goto** 600 !If a component was called too often, go to error handing
		
		6000 **If** (warn) **Then** !if there is no stable solution, print warning and go ahead
		Write(luw,5110) Time
		5110 **Format** (' THERE IS NO STATIONARY STATE AT TIME',F17.12)
		warn = .false.
		Goto 260
		EndIf
		
		Call State(stable,warn) !check if states of controllers were changed
		If (ierror /= 0) **Goto** 999
		If (stable) **Goto** 260 !check the stability
		
		! Restore old values of S and t arrays and return to the beginning of the timestep
		If (iav /= 1) **Then**
		Do i = 1,iav
		S(i) = sstore(i)
		EndDo
		EndIf
		If (nderiv /= 0) **Then**
		last = last1
		corr = corr1
		pred = pred1
		Do i = 1,nderiv
		dtdt(i) = dtstor(i)
		Do j = 1,3
		t(i,j) = tstore(i,j)
		EndDo
		EndDo
		EndIf
		Goto 199
		
		260 intg = 11 !The components have converged - if needed call data exchanger component and check the convergence of the external program
		tCall = 1
		Call Exec(Time,t(1,last),dtdt,intg)
		
		If (CosimConv == .false.) **Then** !If the external program has

		not converged call go back to the beginning of the convergence loop
		
		If (nderiv == 0) Then
		intg = 2
		tCall = 1
		Goto 421
		Else
		intg = 3
		Goto 200
		Endif
		Else
		Goto 270
		Endif
		
		270 Continue !the components have converged - call the after convergence components
		! Call all the converged units again so that they can set their storage variables
		intg = 9
		tCall = 1
		Call Exec(Time,t(1,last),dtdt,intg)
		If (ierror /= 0) Goto 999

Exec	Add variable Call7 in initialization	Use TrnsysData, Only:[…], Call7
	Add a call for Units with info(9) = 6 in the first call manipulations	If (Info(9,unit) == 6) Then Call1(unit) = .true. Call2(unit) = .false. Call3(unit) = .false. Call4(unit) = .false. Call5(unit) = .false. Call7(unit) = .true.

	First call in a standard timestep for all components: set the call array back to true for those components with no connections or unchanged inputs as otherwise they don't get called beyond Time0.	If ((Time < (Time0+1.5d0*delt)).and.(.not.Call1(j)).and.(.not.Call2(j)).and.(.not.Call3(j)).and.(.not.Call4(j)).and.(.not.Call5(j)).and.(.not.Call7(j))) Then
		Call(j) = .true.
		EndIf
		EndDo
		EndIf

	Add a call to *Loopex* when intg = 11 after iterative calls to the components and before post convergence calls	If (intg == 11) Then
		Do j = 1,nunits
		Call(j) = Call7(j)
		Info(13,j) = -2
		EndDo
		Do j = 1,junits
		unit = jcall(j)
		If (unit > 0 .and. Call(unit) .and. Call6(unit)) Then
		ncalls = ncalls + 1
		called(ncalls) = unit
		Call
		LoopEx(unit,j,Call,Time,T_Local,DTDT_Local,lastu,intg)
		If (ierror > 0) Return
		EndIf
		EndDo
		Return
		EndIf

	Add a call for units with info(9) = 6 when the simulation has converged and it is time to call the converged components once more to set storage arrays	! The simulation has converged - call the converged components once more to set storage arrays
		If (intg == 9) Then
		Do j = 1,junits
		unit = jcall(j)
		If ((Info(9,unit) < 2).or.(Info(9,unit)==6)) Then
		Call(unit) = .true.
		Else
		Call(unit) = .false.
		EndIf
		Info(13,unit) = 1
		EndDo

Loopex	•Add variable "CosimConvergenceChecking Time" during initialization.	Use TrnsysData, Only: […], CosimConvergenceCheckingTime

	Update the variable
	"CosimConvergenceChecking Time"
		If (Info(13,unit) == -2) Then
		CosimConvergenceCheckingTime = .true.
		Else
		CosimConvergenceCheckingTime = .false.
		EndIf

ADDITIONAL MODIFICATIONS:

NEW ACCESS FUNCTIONS FOR CONTROLLERS IN CO-SIMULATIONS

Subroutine	Modifications	Code
TrnsysData	Add invocations and iterations counter for co-simulations	!invocations counter (co-simulation) Integer :: CosimInvocation = 0 !iterations per invocation counter (co-simulation) Integer :: CosimInvocationIteration = 0 !New invocation flag Logical :: CosimNewInvocation = .true.
TrnsysFunctions	Add functions : - getCosimInvocation - getCosimInvocationIteration - getIsCosimNewInvocation	! getCosimInvocation Function getCosimInvocation() !dec$ attributes dllexport :: getCosimInvocation Use TrnsysData, Only: CosimInvocation Implicit None Integer getCosimInvocation getCosimInvocation = CosimInvocation End Function getCosimInvocation ! getCosimInvocationIteration Function getCosimInvocationIteration() !dec$ attributes dllexport :: getCosimInvocationIteration Use TrnsysData, Only: CosimInvocationIteration

		Implicit None Integer getCosimInvocationIteraion getCosimInvocationIteration = CosimInvocationIteration End Function getCosimInvocationIteration ! getIsCosimNewInvocation Function getIsCosimNewInvocation() !dec$ attributes dllexport :: getIsCosimNewInvocation Use TrnsysData, Only: CosimNewInvocation Implicit None Integer getIsCosimNewInvocation getIsCosimNewInvocation = CosimNewInvocation End Function getIsCosimNewInvocation

Type2	Reset the iteration counter after each invocation for preventing the controller from being stuck after some invocations	!Check number of iterations. Out(3) - iosc is stick counter. Out(2) is counting total number of times in simulation stick occurs
		If (nstk>0) Then !Solver 0 control strategy
		If (getTimestepIteration()==0 .OR. getCosimInvocationIteration()==0) Call SetOutputValue(3,0.d0) !Clear stick counter on first call of timestep
		clast = getOutputValue(1)
		iosc = JFIX(getOutputValue(3)+0.01)
		If (iosc==nstk) Call SetOutputValue(2,getOutputValue(2)+1.d0)
		If (iosc<nstk) Then
		cntold = getOutputValue(4)
		If (getTimestepIteration()==0 .OR. getCosimInvocationIteration()==0) Then
		If (getInputValue(4)>0.5) Then

		cntold = 1
		Call SetOutputValue(4,DBLE(cntold))
		Else
		cntold = 0
		Call SetOutputValue(4,DBLE(cntold))
		EndIf
		EndIf

ANNEX 3 – TYPE 130 CODE

```
Subroutine Type130

! Author: Romain Jost, Timothy McDowel, Michaël Kummert
! Date:        April 28, 2011
! last modified: July 06, 2012
!-------------------------------------------------------------------------------------------
--------------------------
Use TrnsysConstants
Use TrnsysFunctions
Use DFWIN
Use DFLIB
Use TrnsysData, Only:CosimConv, Info, CosimInvocation, CosimInvocationIteration,
CosimNewInvocation
use CosimDataTypes
!-------------------------------------------------------------------------------------------
--------------------------
!export this subroutine for its use in external DLLs
!DEC$Attributes DLLexport :: Type130
!-------------------------------------------------------------------------------------------
--------------------------
!Declarations
Implicit None

Double Precision Timestep,Time
Integer CurrentUnit,CurrentType
Integer, Parameter :: nDblMax = 100      !Maximum number of inputs/outputs
Integer i !Loop counter
Integer c !Loop counter in HarmonizerTest
Double precision HR !Humidity ratio (Temporary variable)
Double precision AirFlow !Air flowrate (Temporary variable)
Integer NumIn !Number of inputs (in order to transfer data to Espr, to be coded...)
Integer NumOut !Number of outputs
Integer TSiterations !Number of Type 130 iterations per time step
Integer N1 !Mode (0 normal, 1 test mode)
Integer N2 !Nb of zones
Integer N3 !Nb of HccToTrnsys
Integer N4 !Nb of HccToEspr
Integer N5 !Nb of AccToTrnsys
Integer N6 !Nb of AccToEspr
Integer N7 !Nb of forced invocations in test mode
Integer SystemConverged !True: Espr has converged, false Espr has not converged
Pointer (HarmonizerHandle, Harmonizer)  ! HarmonizerHandle will be a handle to the
Harmonizer library.
Pointer (GetEsprDataAddress, GetEsprData) ! GetEsprDataAddress will be pointing to the
address of the GetEsprData routine in Harmonizer
Pointer (PassDataToEsprAddress, PassDataToEspr) ! PassDataToEsprAddress will be pointing
to the address of the PassDataToEspr routine in Harmonizer
Pointer (GetSystemConvAddress, GetSystemConv) ! GetSystemConvAddress will be pointing to
the address of the GetSystemConv routine in Harmonizer
Integer (INT_PTR_KIND()) :: HarmonizerHandle, PassDataToEsprAddress, GetEsprDataAddress,
GetSystemConvAddress
Character (len=maxPathLength) :: Harmonizer
Type(EsprTrnsysData) :: CosimData
!-------------------------------------------------------------------------------------------
--------------------------
```

```
!Get the Global Trnsys Simulation Variables
Time=getSimulationTime()
Timestep=getSimulationTimeStep()
!------------------------------------------------------------------------------------------
-------------------------
!Tell harmonizer where Trnsys is in the simulation
 CosimData%TrnsysTimestep = JFIX(Time/Timestep+ 0.1d0)

!Tell Trnsys where the co-simulation is
CosimInvocationIteration = CosimInvocationIteration + 1
If (CosimInvocationIteration > 1 ) Then
 CosimNewInvocation = .false.
EndIf
!------------------------------------------------------------------------------------------
-------------------------
!Set the Version Number for This Type
If(getIsVersionSigningTime()) Then

 Call SetTypeVersion(17)

 Return
EndIf
!------------------------------------------------------------------------------------------
-------------------------
!Do Any Last Call Manipulations Here
If(getIsLastCallofSimulation()) Then

! Get values from Type 130 inputs
 Do i = 1, N2
   CosimData%ESPrZonesData(i)%AirPointCasualGains = getInputValue(i)/3.6 !includes
conversion kJ/h -> W
 EndDo
 Do i = 1, N4
   CosimData%HCC_to_ESPr(i)%Temperature = getInputValue(N2+2*i-1)
   CosimData%HCC_to_ESPr(i)%Flowrate = getInputValue(N2+2*i)/3600 !includes conversion
kg/h -> kg/s
 EndDo
 Do i = 1, N6
  CosimData%ACC_to_ESPr(i)%Temperature = getInputValue(N2+N4*2+3*i-2)
  HR = getInputValue(N2+N4*2+3*i-1)
  AirFlow = getInputValue(N2+N4*2+3*i)/3600
  CosimData%ACC_to_ESPr(i)%Flowrate = AirFlow !includes conversion kg/h -> kg/s
  CosimData%ACC_to_ESPr(i)%Moisture_flowrate = HR*AirFlow
 EndDo

 CosimData%TrnsysTimestep = JFIX(Time/Timestep+ 0.1d0) !Tell harmonizer where Trnsys is in
the simulation

! Pass data to Esp-r
Call PassDataToEspr(CosimData)

 Return
EndIf
!------------------------------------------------------------------------------------------
-------------------------
!Perform Any "After Convergence" Manipulations That May Be Required at the End of Each
Timestep
If(getIsEndOfTimestep()) Then
```

```
 Return
EndIf
!-----------------------------------------------------------------------------------------
--------------------------
!Do All of the "Very First Call of the Simulation Manipulations" Here
If(getIsFirstCallofSimulation()) Then

CosimInvocationIteration = 0 !Initialization iterations per invocation counter

 c = 0 !Initialization of invocations loop counter in test mode

! Get the number of components
 N1 = JFIX(GetParameterValue(1)+ 0.1d0) !Mode
 N2 = JFIX(GetParameterValue(2)+ 0.1d0) !Number of zones
 N3 = JFIX(GetParameterValue(3)+ 0.1d0) !Number of HccToTrnsys
 N4 = JFIX(GetParameterValue(4)+ 0.1d0) !Number of HccToEspr
 N5 = JFIX(GetParameterValue(5)+ 0.1d0) !Number of AccToTrnsys
 N6 = JFIX(GetParameterValue(6)+ 0.1d0) !Number of AccToEspr
 If (N1 == 1) Then
  N7 = JFIX(GetParameterValue(7)+ 0.1d0) !Number of forced invocations for testing (mode =
1)
 EndIf

 NumIn = N2 + N4*2 + N6*3 !Number of inputs
 NumOut = N2*2 + N3*2 + N5*3 !Number of outputs

 If (NumIn < 0) Call FOUNDBADPARAMETER(1,'Fatal','The number of input values cannot be
less than 0.')
 If (NumIn > nDblMax) Call FOUNDBADPARAMETER(1,'Fatal','The number of input values is set
higher than the maximum allowed.')
 If (NumOut < 0) Call FOUNDBADPARAMETER(1,'Fatal','The number of output values cannot be
less than 0.')
 If (NumOut > nDblMax) Call FOUNDBADPARAMETER(1,'Fatal','The number of output values is
set higher than the maximum allowed.')

!Tell the TRNSYS Engine How This Type Works
 Call SetNumberofParameters(6 + N1)              !The number of parameters that the the
model wants
 Call SetNumberofInputs(NumIn)                   !The number of inputs that the the model
wants
 Call SetNumberofDerivatives(0)                  !The number of derivatives that the the
model wants
 Call SetNumberofOutputs(NumOut)                 !The number of outputs that the the model
produces
 Call SetIterationMode(6)                        !An indicator for the iteration mode
(default=1).
 Call SetNumberStoredVariables(0,0)              !The number of static variables that the
model wants stored in the global storage array and the number of dynamic variables that
the model wants stored in the global storage array
 Call SetNumberofDiscreteControls(0)             !The number of discrete control functions
set by this model (a value greater than zero requires the user to use Solver 1: Powell's
method)

! Set the Correct Input and Output Variable Types
 Do i = 1, NumIn
  Call SETINPUTUNITS(i,'NAV')
 EndDo
```

```
 Do i = 1,NumOut
  Call SETOUTPUTUNITS(i,'NAV')
 EndDo

 If (N1 == 0) Then !Standard mode (0)
! Load the standard Harmonizer DLL
  HarmonizerHandle = LoadLibrary('Harmonizer.dll'//""C)
  If(HarmonizerHandle <= 0) then
   Call Messages(-1,'Harmonizer.dll can not be loaded','FATAL',CurrentUnit,CurrentType)
   Return
  EndIf

 ElseIf (N1 == 1) Then ! Test mode (1)
! Load the HarmonizerTest DLL
  HarmonizerHandle = LoadLibrary('HarmonizerTest.dll'//""C)
  If(HarmonizerHandle <= 0) then
   Call Messages(-1,'HarmonizerTest.dll can not be
loaded','FATAL',CurrentUnit,CurrentType)
   Return
  EndIf

 Else
  Call Messages(-1,'Mode number must be equal to 0 or 1','FATAL',CurrentUnit,CurrentType)
 EndIf

! Get a pointer to the GetEsprData subroutine address
 GetEsprDataAddress = GetProcAddress(HarmonizerHandle,"GETESPRDATA"C) !REVISIT: error out
on failure
 If(GetEsprDataAddress <= 0) then
  Call Messages(-1,'GetEsprData function can not be
loaded','FATAL',CurrentUnit,CurrentType)
  Return    ! GetEsprData subroutine was not found
 EndIf

! Get a pointer to the procedure address that we want to call (the PassDataToEspr
subroutine)
 PassDataToEsprAddress = GetProcAddress(HarmonizerHandle,"PASSDATATOESPR"C) !REVISIT:
error out on failure
 If(PassDataToEsprAddress <= 0) then
  Call Messages(-1,'PassDataToEspr function can not be
loaded','FATAL',CurrentUnit,CurrentType)
  Return    ! PassDataToEspr subroutine was not found
 EndIf

! Get a pointer to the GetSystemConv subbroutine address
 GetSystemConvAddress = GetProcAddress(HarmonizerHandle,"GETSYSTEMCONV"C) !REVISIT: error
out on failure
 If(GetSystemConvAddress <= 0) then
  Call Messages(-1,'GetSystemConv function can not be
loaded','FATAL',CurrentUnit,CurrentType)
  Return    ! GetSystemConv subroutine was not found
 EndIf

 Return
EndIf
!-------------------------------------------------------------------------------------
-------------------------! Do All of the First Timestep Manipulations Here - There Are No
Iterations at the Intial Time
```

```
If (getIsStartTime()) Then

! Get values from Type 130 inputs
 Do i = 1, N2
   CosimData%ESPrZonesData(i)%AirPointCasualGains = getInputValue(i)/3.6 !includes
conversion kJ/h -> W
 EndDo
 Do i = 1, N4
   CosimData%HCC_to_ESPr(i)%Temperature = getInputValue(N2+2*i-1)
   CosimData%HCC_to_ESPr(i)%Flowrate = getInputValue(N2+2*i)/3600 !includes conversion
kg/h -> kg/s
 EndDo
 Do i = 1, N6
  CosimData%ACC_to_ESPr(i)%Temperature = getInputValue(N2+N4*2+3*i-2)
  HR = getInputValue(N2+N4*2+3*i-1)
  AirFlow = getInputValue(N2+N4*2+3*i)/3600
  CosimData%ACC_to_ESPr(i)%Flowrate = AirFlow !includes conversion kg/h -> kg/s
  CosimData%ACC_to_ESPr(i)%Moisture_flowrate = HR*AirFlow
 EndDo

!Tell harmonizer where Trnsys is in the simulation
 CosimData%TrnsysTimestep = JFIX(Time/Timestep+ 0.1d0)
 CosimData%TotalTrnsysIterations = TSiterations

 Call PassDataToEspr(CosimData) !Send data to the Harmonizer

 If (N1 == 0) Then
  Call GetEsprData(CosimData) !Receive data from the Harmonizer
 Else
  Call GetEsprData(CosimData,c,N7) !Receive data from the fake Harmonizer (test mode)
 EndIf

! Set Type 130 outputs values
 Do i = 1, N2
  Call SetOutputValue(2*i-1,CosimData%ESPrZonesData(i)%AirPointTemperature)
  Call SetOutputValue(2*i,CosimData%ESPrZonesData(i)%AirPointHumidity)
 EndDo
 Do i = 1, N3
  Call SetOutputValue(N2*2+2*i-1,CosimData%HCC_to_TRNSYS(i)%Temperature)
  Call SetOutputValue(N2*2+2*i,CosimData%HCC_to_TRNSYS(i)%Flowrate * 3600) !includes
conversion kg/s -> kg/hr
 EndDo
 Do i = 1, N5
  Call SetOutputValue(N2*2+N3*2+3*i-2,CosimData%ACC_to_TRNSYS(i)%Temperature)
  If (CosimData%ACC_to_TRNSYS(i)%Flowrate == 0) Then
   Call SetOutputValue(N2*2+N3*2+3*i-1, 0d0)
  Else
   Call SetOutputValue(N2*2+N3*2+3*i-1,CosimData%ACC_to_TRNSYS(i)%Moisture_flowrate /
CosimData%ACC_to_TRNSYS(i)%Flowrate) !includes conversion Moisture_flowrate (kg/s) ->
Humidity ratio
  Endif
  Call SetOutputValue(N2*2+N3*2+3*i,CosimData%ACC_to_TRNSYS(i)%Flowrate * 3600) !includes
conversion kg/s -> kg/hr
 Enddo

 Return
EndIf
```

```
!-------------------------------------------------------------------------------------------
-------------------------
!ReRead the Parameters if Another Unit of This Type Has Been Called Last
If(getIsReReadParameters()) Then

 Call MESSAGES(-1,'Only one data exchanger componenent is allowed per
project.','FATAL',CurrentUnit,CurrentType)

 Return
EndIf
!-------------------------------------------------------------------------------------------
-------------------------
If(ErrorFound()) Return
!-------------------------------------------------------------------------------------------
-------------------------
!TRNSYS has converged - check if the ESP-r has converged
If (getIsCosimConvergenceCheckingTime()) Then

!Tell harmonizer where Trnsys is in the simulation
 CosimData%TrnsysConverged = 1
 CosimData%TrnsysTimestep = JFIX(Time/Timestep+ 0.1d0)
 CosimData%TotalTrnsysIterations = TSiterations + getTimestepIteration()

 Call PassDataToEspr(CosimData) !Send data to the Harmonizer

 If (N1 == 0) Then !Standard mode (0)
  Call GetSystemConv(SystemConverged)
 Else !Test mode (1)
  Call GetSystemConv(SystemConverged,c,N7)
 EndIf

 CosimInvocationIteration = 0

 If (SystemConverged == 1) Then
  CosimConv = .True.
  TSiterations = 0
  CosimInvocation = 0
  CosimNewInvocation = .false.
 Else
  CosimConv = .False.
  TSiterations = CosimData%TotalTrnsysIterations
  CosimInvocation = CosimInvocation + 1
  CosimNewInvocation = .true.


  If (N1 == 0) Then !Standard mode (0)
   Call GetEsprData(CosimData) !Receive data from the Harmonizer
  Else !Test mode (1)
   Call GetEsprData(CosimData,c,N7)!Receive data from the fake Harmonizer
  EndIf
EndIf

! Set Type 130 outputs values
 Do i = 1, N2
  Call SetOutputValue(2*i-1,CosimData%ESPrZonesData(i)%AirPointTemperature)
  Call SetOutputValue(2*i,CosimData%ESPrZonesData(i)%AirPointHumidity)
 EndDo
 Do i = 1, N3
```

```
  Call SetOutputValue(N2*2+2*i-1,CosimData%HCC_to_TRNSYS(i)%Temperature)
  Call SetOutputValue(N2*2+2*i,CosimData%HCC_to_TRNSYS(i)%Flowrate * 3600) !includes
conversion kg/s -> kg/hr
 EndDo
 Do i = 1, N5
  Call SetOutputValue(N2*2+N3*2+3*i-2,CosimData%ACC_to_TRNSYS(i)%Temperature)
  If (CosimData%ACC_to_TRNSYS(i)%Flowrate == 0) Then
   Call SetOutputValue(N2*2+N3*2+3*i-1, 0d0)
  Else
   Call SetOutputValue(N2*2+N3*2+3*i-1,CosimData%ACC_to_TRNSYS(i)%Moisture_flowrate /
CosimData%ACC_to_TRNSYS(i)%Flowrate) !includes conversion Moisture_flowrate (kg/s) ->
Humidity ratio
  EndIf
  Call SetOutputValue(N2*2+N3*2+3*i,CosimData%ACC_to_TRNSYS(i)%Flowrate * 3600) !includes
conversion kg/s -> kg/hr
 EndDo

 CosimData%TrnsysConverged = 0

 Return
EndIf
!-------------------------------------------------------------------------------------------
--------------------------
!Get data from ESP-r at the beginning of each time step
If (getTimestepIteration() == 0) Then

 !Tell harmonizer where Trnsys is in the simulation
 CosimData%TrnsysTimestep = JFIX(Time/Timestep+ 0.1d0) !Tell harmonizer where Trnsys is in
the simulation
 CosimData%TotalTrnsysIterations = TSiterations + getTimestepIteration()

 If (N1 == 0) Then !Standard mode (0)
  Call GetEsprData(CosimData) !Receive data from the Harmonizer
 Else !Test mode (1)
  Call GetEsprData(CosimData,c,N7) !Receive data from the fake Harmonizer
 EndIf

 ! Set Type 130 outputs values
 Do i = 1, N2
  Call SetOutputValue(2*i-1,CosimData%ESPrZonesData(i)%AirPointTemperature)
  Call SetOutputValue(2*i,CosimData%ESPrZonesData(i)%AirPointHumidity)
 EndDo
 Do i = 1, N3
  Call SetOutputValue(N2*2+2*i-1,CosimData%HCC_to_TRNSYS(i)%Temperature)
  Call SetOutputValue(N2*2+2*i,CosimData%HCC_to_TRNSYS(i)%Flowrate * 3600) !includes
conversion kg/s -> kg/hr
 Enddo
 Do i = 1, N5
  Call SetOutputValue(N2*2+N3*2+3*i-2,CosimData%ACC_to_TRNSYS(i)%Temperature)
  If (CosimData%ACC_to_TRNSYS(i)%Flowrate == 0) Then
   Call SetOutputValue(N2*2+N3*2+3*i-1, 0d0)
  Else
   Call SetOutputValue(N2*2+N3*2+3*i-1,CosimData%ACC_to_TRNSYS(i)%Moisture_flowrate /
CosimData%ACC_to_TRNSYS(i)%Flowrate) !includes conversion Moisture_flowrate (kg/s) ->
Humidity ratio
  EndIf
  Call SetOutputValue(N2*2+N3*2+3*i,CosimData%ACC_to_TRNSYS(i)%Flowrate * 3600) !includes
conversion kg/s -> kg/hr
```

```
 EndDo

EndIf
!-------------------------------------------------------------------------------------------
--------------------------
!Do every iterations Manipulations Here

! Get values from Type 130 inputs
 Do i = 1, N2
   CosimData%ESPrZonesData(i)%AirPointCasualGains = getInputValue(i)/3.6 !includes
conversion kJ/h -> W
 EndDo
 Do i = 1, N4
   CosimData%HCC_to_ESPr(i)%Temperature = getInputValue(N2+2*i-1)
   CosimData%HCC_to_ESPr(i)%Flowrate = getInputValue(N2+2*i)/3600 !includes conversion
kg/h -> kg/s
 EndDo
 Do i = 1, N6
  CosimData%ACC_to_ESPr(i)%Temperature = getInputValue(N2+N4*2+3*i-2)
  HR = getInputValue(N2+N4*2+3*i-1)
  AirFlow = getInputValue(N2+N4*2+3*i)/3600
  CosimData%ACC_to_ESPr(i)%Flowrate = AirFlow !includes conversion kg/h -> kg/s
  CosimData%ACC_to_ESPr(i)%Moisture_flowrate = HR*AirFlow
 EndDo

! Set Type 130 outputs values
 Do i = 1, N2
  Call SetOutputValue(2*i-1,CosimData%ESPrZonesData(i)%AirPointTemperature)
  Call SetOutputValue(2*i,CosimData%ESPrZonesData(i)%AirPointHumidity)
 EndDo
 Do i = 1, N3
  Call SetOutputValue(N2*2+2*i-1,CosimData%HCC_to_TRNSYS(i)%Temperature)
  Call SetOutputValue(N2*2+2*i,CosimData%HCC_to_TRNSYS(i)%Flowrate * 3600) !includes
conversion kg/s -> kg/hr
 EndDo
 Do i = 1, N5
  Call SetOutputValue(N2*2+N3*2+3*i-2,CosimData%ACC_to_TRNSYS(i)%Temperature)
  If (CosimData%ACC_to_TRNSYS(i)%Flowrate == 0) Then
   Call SetOutputValue(N2*2+N3*2+3*i-1, 0d0)
  Else
   Call SetOutputValue(N2*2+N3*2+3*i-1,CosimData%ACC_to_TRNSYS(i)%Moisture_flowrate /
CosimData%ACC_to_TRNSYS(i)%Flowrate) !includes conversion Moisture_flowrate (kg/s) ->
Humidity ratio
  EndIf
  Call SetOutputValue(N2*2+N3*2+3*i,CosimData%ACC_to_TRNSYS(i)%Flowrate * 3600) !includes
conversion kg/s -> kg/hr
 Enddo
!-------------------------------------------------------------------------------------------
--------------------------

  Return
End
```